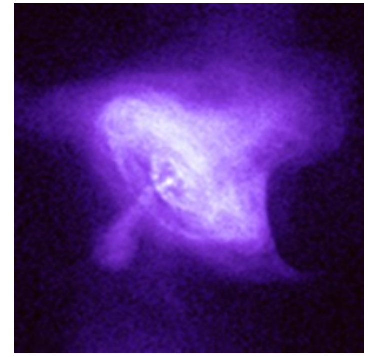
How do pulsars shine?

Sasha Philippov (Princeton University)

Collaborators: Anatoly Spitkovsky (Princeton), Benoit Cerutti (CNRS), Sasha Tchekhovskoy (Berkeley)

Open questions:



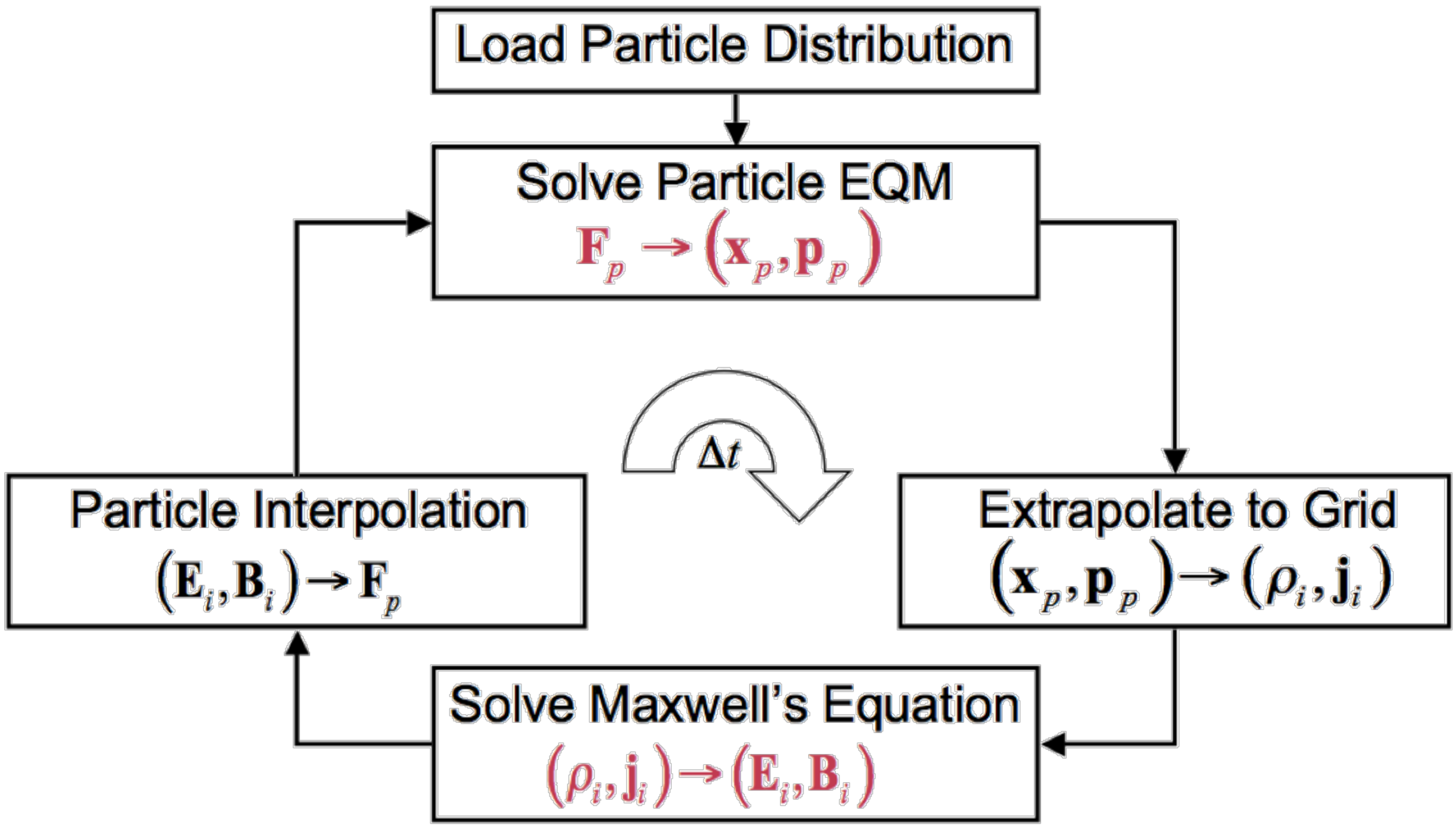
- How pulsar magnetosphere works?
    - Nebula observations favor plasma-filled magnetospheres
- How particle acceleration works?
- How pulsars shine?
    - Most of the observable energy comes in gamma-rays
- How pulsars evolve?

PIC simulation of magnetospheres I

- Core - EM PIC codes TRISTAN-MP (Spitkovsky 2008) and Zeltron (Cerutti et. al., 2014).

$$\partial E/\partial t = c(\nabla \times B) - 4\pi J\,, \qquad \nabla \cdot E = 4\pi\varrho\,, \quad \nabla \cdot B = 0$$

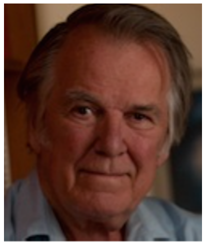
$$\partial B/\partial t = -c(\nabla \times E)\,, \qquad \frac{d}{dt}\gamma m\mathbf{v} = q(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B})$$



Jump-starting the pulsar: regimes of plasma supply

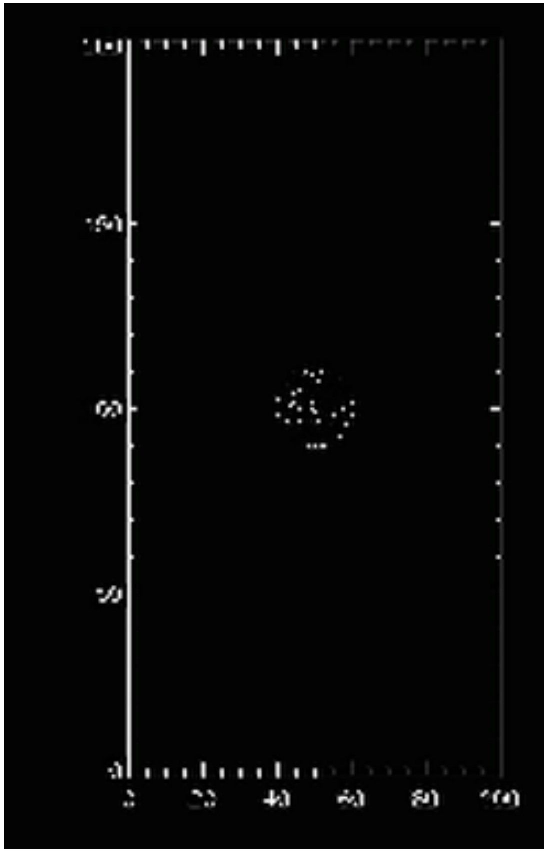
- Availability of plasma supply and whether magnetosphere is filled with plasma can determine the properties of spin-down and radiation. We tried:
  - Free particle escape from the surface without pair production.
  - Free escape with pair production: aligned and oblique rotators.
  - Modifications of pair supply in GR.

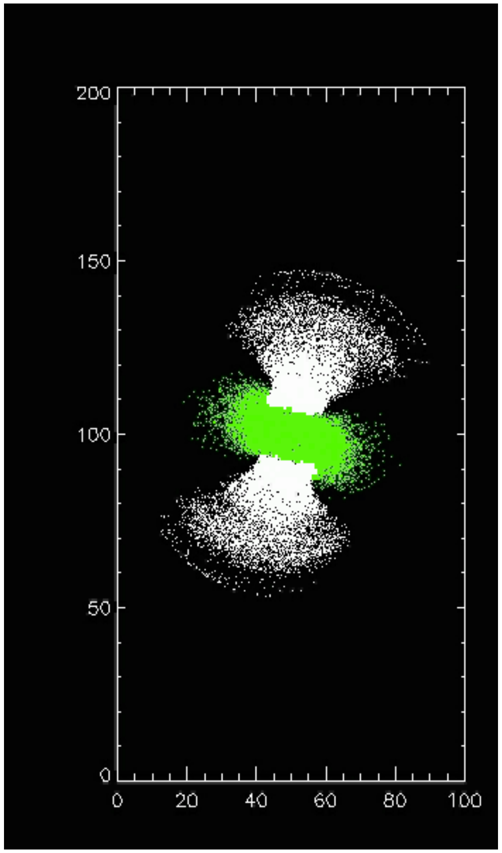
Electrostatically trapped solution



C. Michel

- Only free escape from the surface
- Disk-dome solution
- Almost no outflow and spin-down





Kraus-Polstorff & Michel, 1985; Spitkovsky & Arons, 2002; Petri et al., 2002; Philippov & Spitkovsky, 2014

PIC simulation of magnetospheres II

- Core - EM PIC codes TRISTAN-MP (Spitkovsky 2008) and Zeltron (Cerutti et. al., 2014).
- Conducting BC at the stellar surface, “absorbing layer” BC at the outer edge. Provide free escape of particles (both electrons and ions) from the surface.
- Radiative cooling is implemented for particle motion. To get correct cooling rates, need to resolve Larmor gyrations in time.

$$\mathbf{g} = \frac{2}{3} r_e^2 \left[(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B}) \times \mathbf{B} + (\boldsymbol{\beta} \cdot \mathbf{E}) \mathbf{E} \right] - \frac{2}{3} r_e^2 \gamma^2 \left[(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B})^2 - (\boldsymbol{\beta} \cdot \mathbf{E})^2 \right] \boldsymbol{\beta}$$

- Pair creation with the threshold based on particle energy. Recently added tracking of photons and the pair formation threshold based on photon energy.
- Effects of GR: simulations in slowly rotating metric.
- Scales approached:

$$R_*/(c/\omega_p) \approx 30 - 40 \gg 1 \qquad R_{LC}/R_* = 3 - 5$$

$$\Phi_{PC} = \mu \Omega^2 / c^2 \approx 500 \gg \gamma_{\text{threshold}} = 40$$

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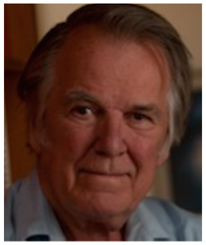

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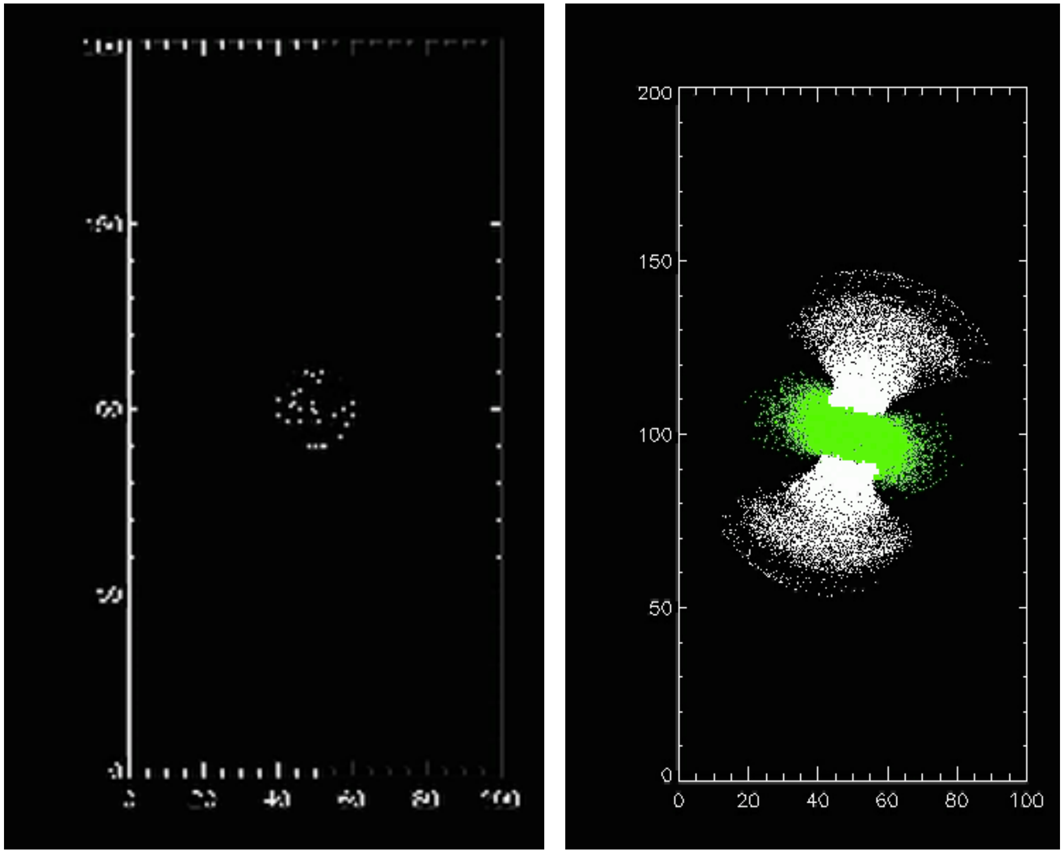

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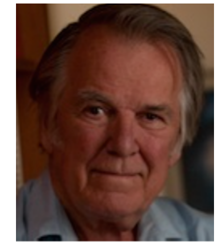

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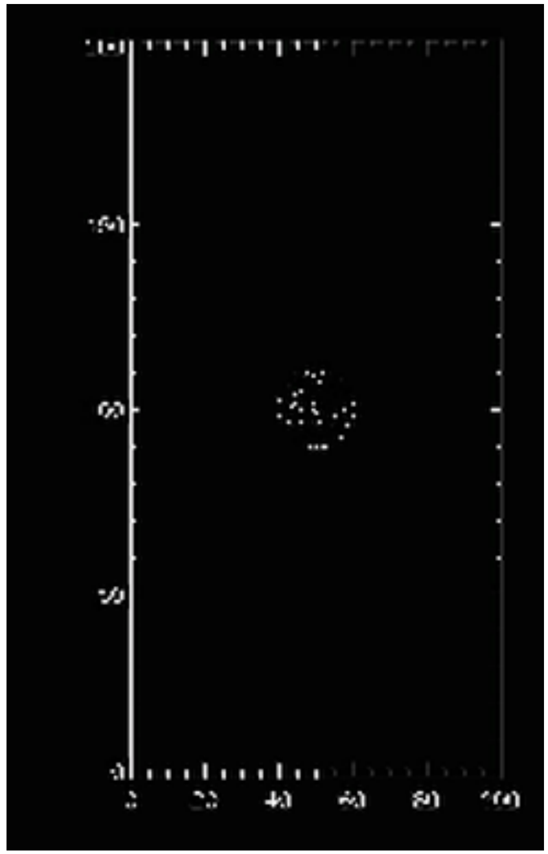
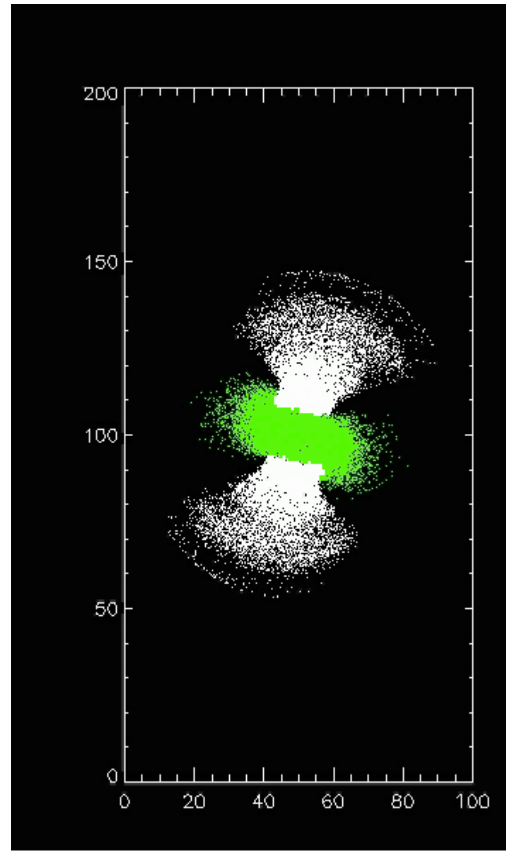
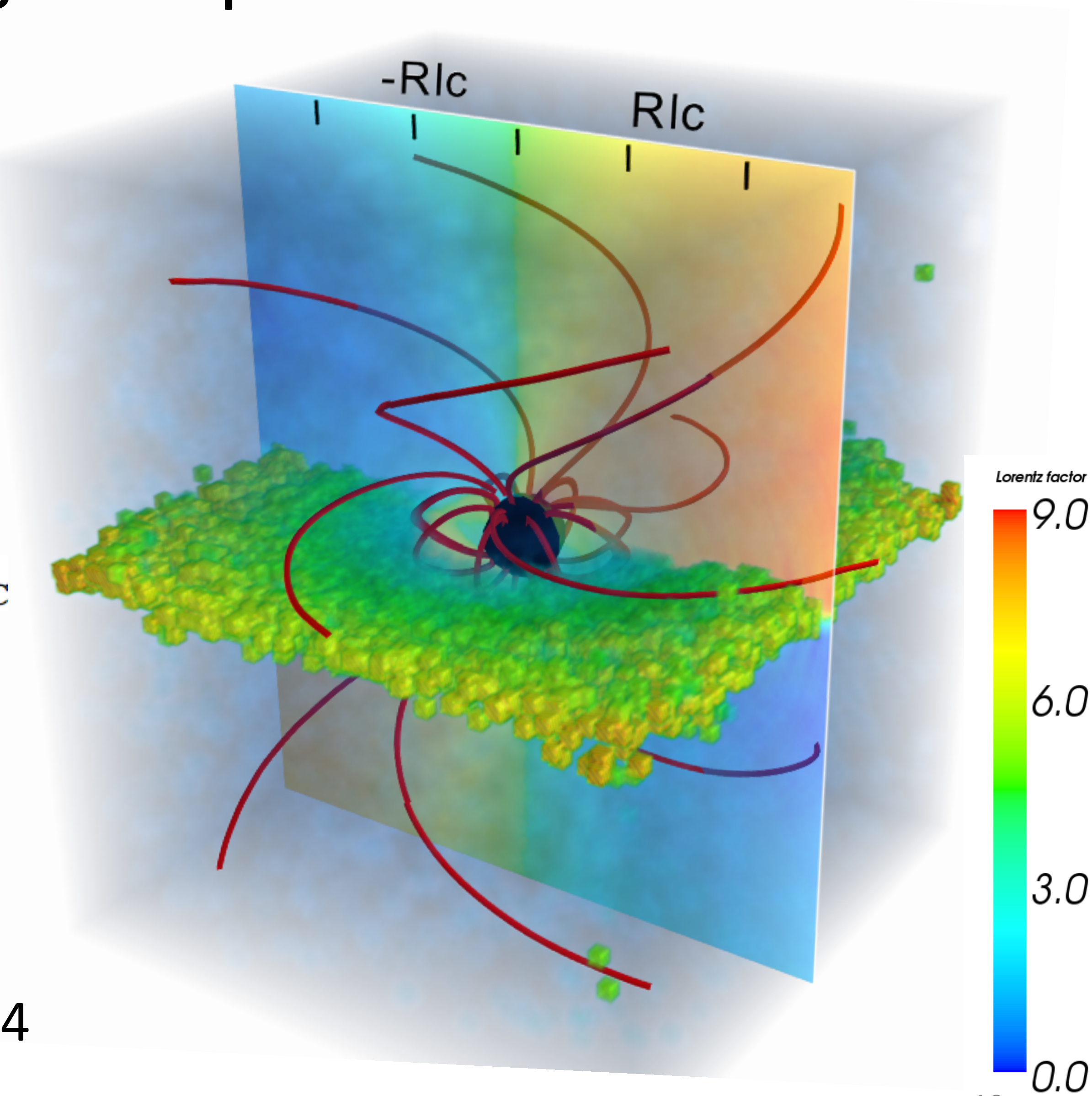




Kraus-Polstorff & Michel, 1985; Spitkovsky & Arons, 2002; Petri et al., 2002; Philippov & Spitkovsky, 2014

Volumetric pair supply in the aligned magnetosphere

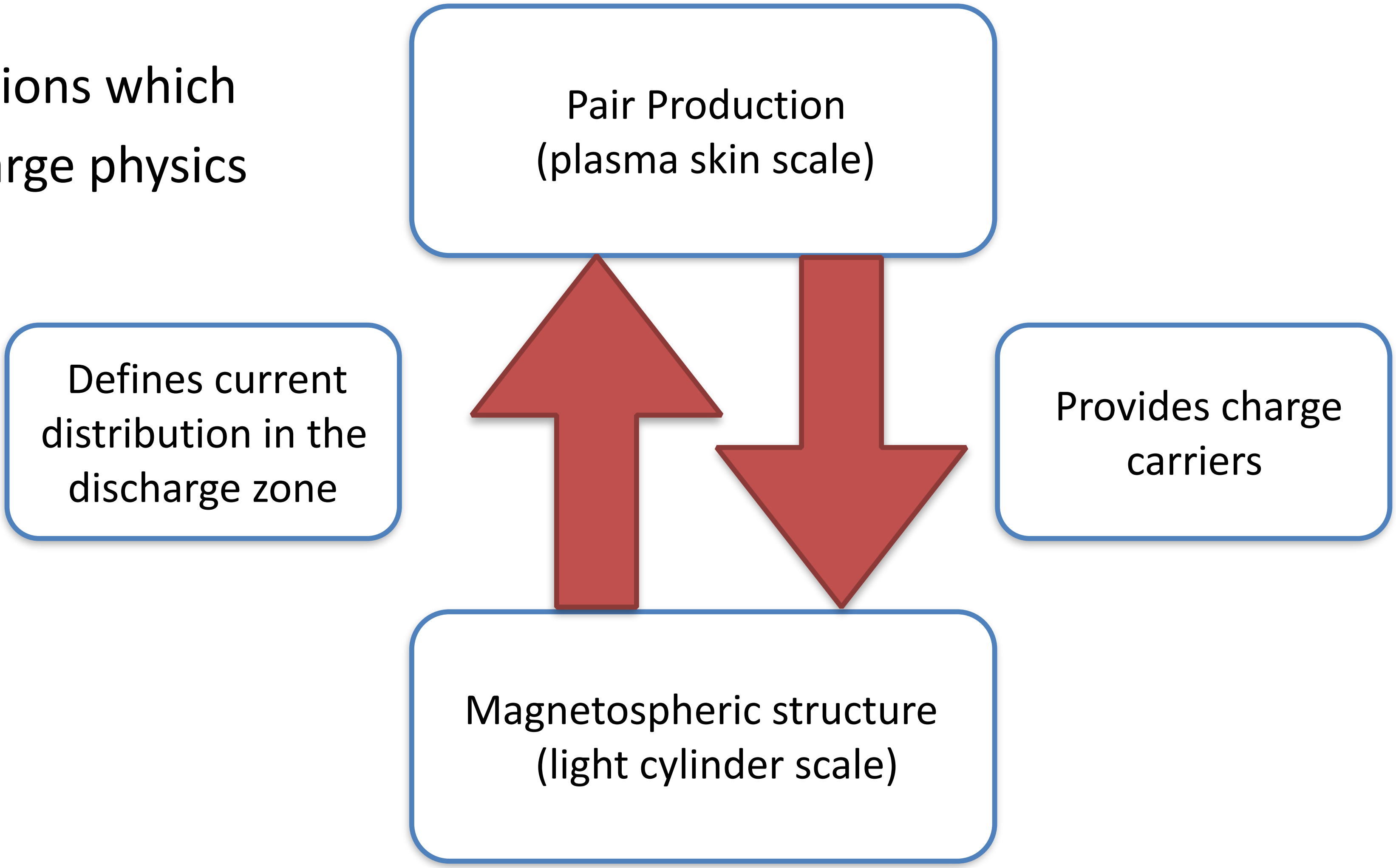
- Approaches force-free
- Self-consistent current sheet
- 15% of Poynting flux is dissipated within $2R_{LC.}$
- Observed drift-kink instability of the current sheet.
- Particles are accelerated up to σ_{LC} energies.



Philippov & Spitkovsky, ApJ, 2014

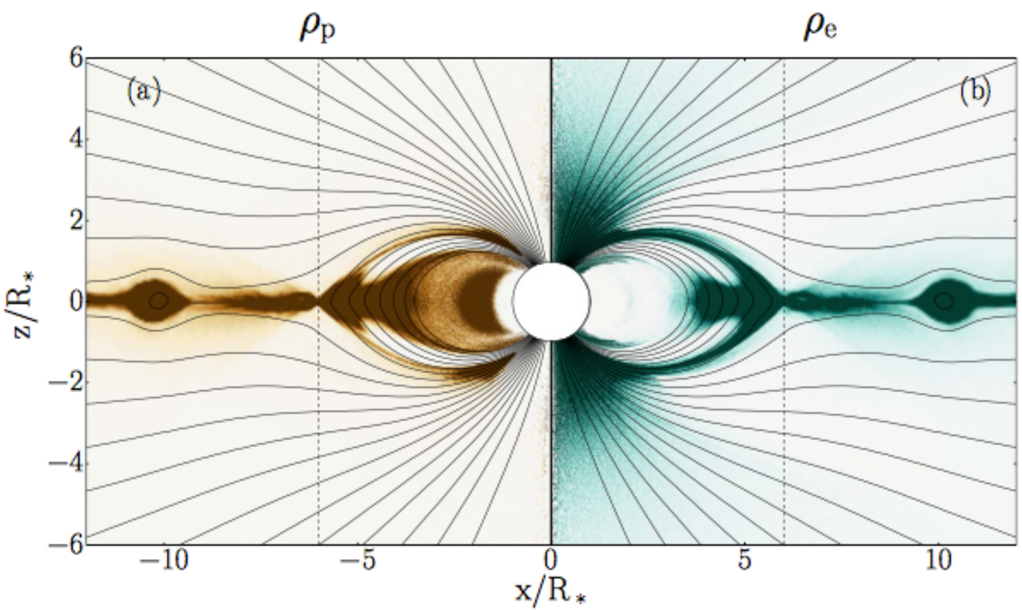
Magnetosphere is a self-regulated system

Global simulations which capture discharge physics are required!



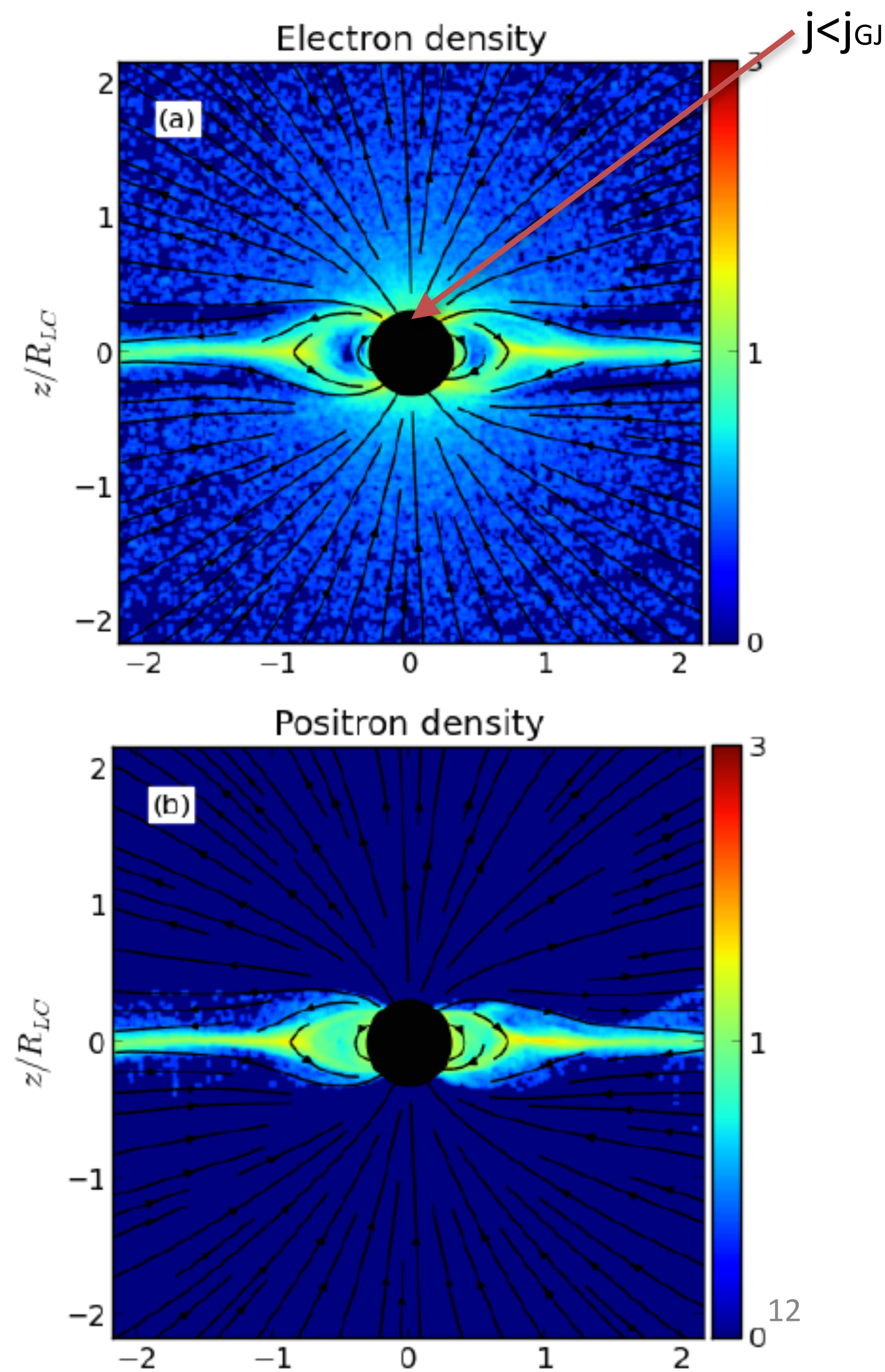
Aligned pulsar with pair production

Approaches force-free like solution, but no pair production in the polar region, where the space-charge limited flow does not lead to particle acceleration. Outer magnetosphere pair production is required to drive an active circuit.



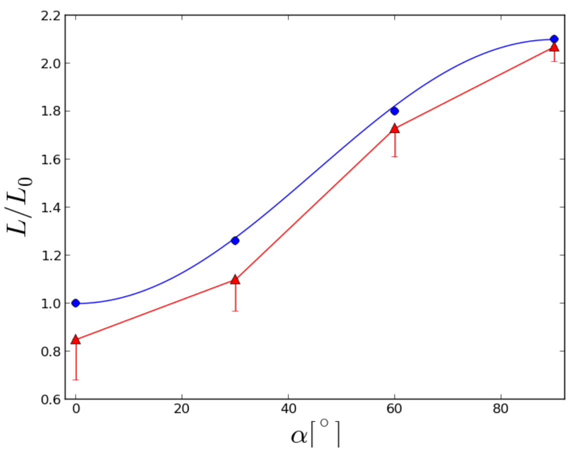
Chen, Beloborodov, ApJ, 2014

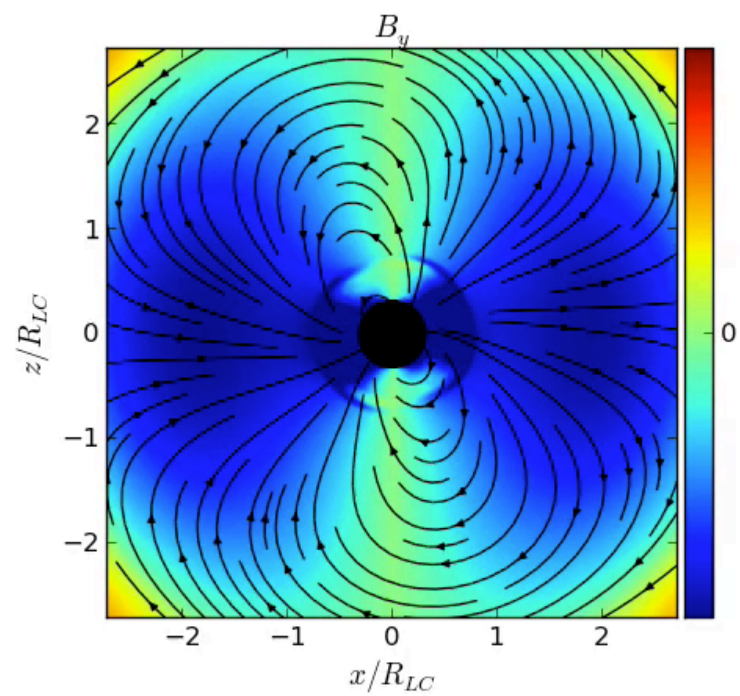
Philippov et al., ApJ, 2015



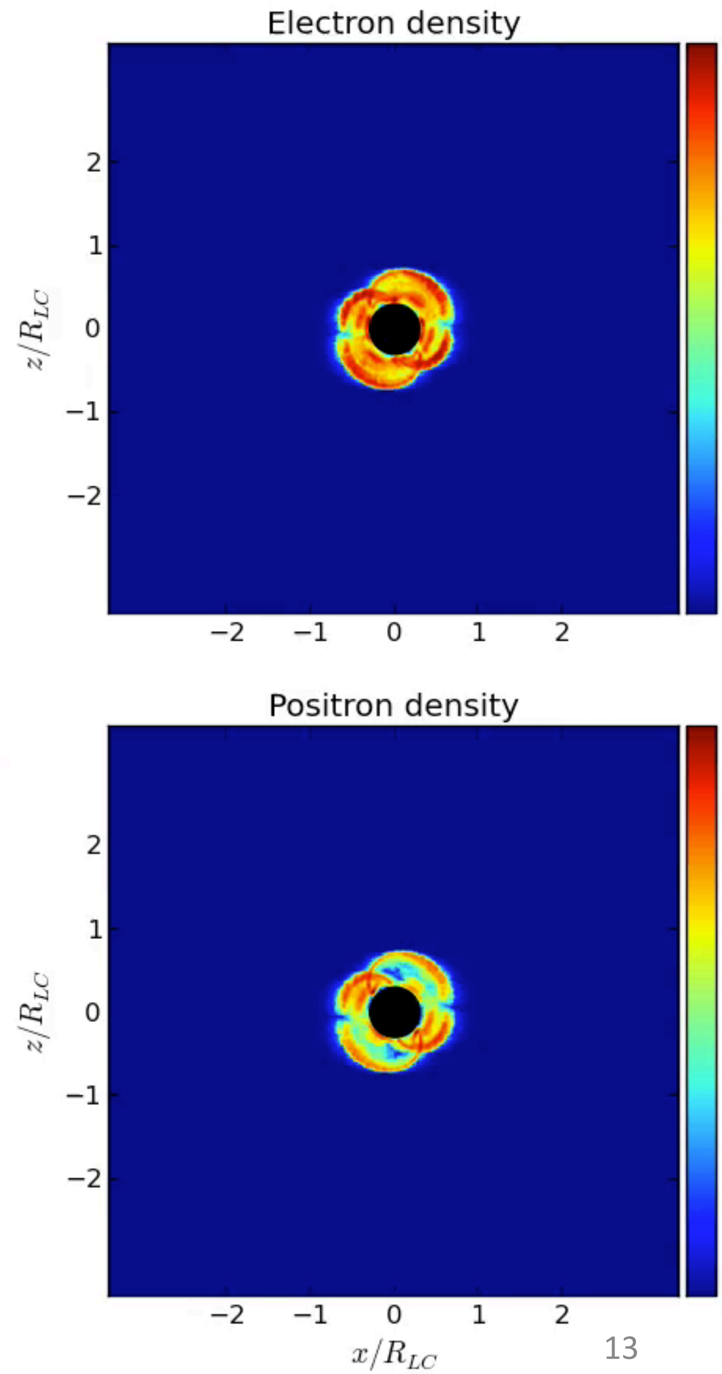
Oblique pulsar with pair production

- Approaches force-free like solution.
- Pairs are produced only in the part of the polar cap.
- Dissipation decreases as a function of the inclination angle.



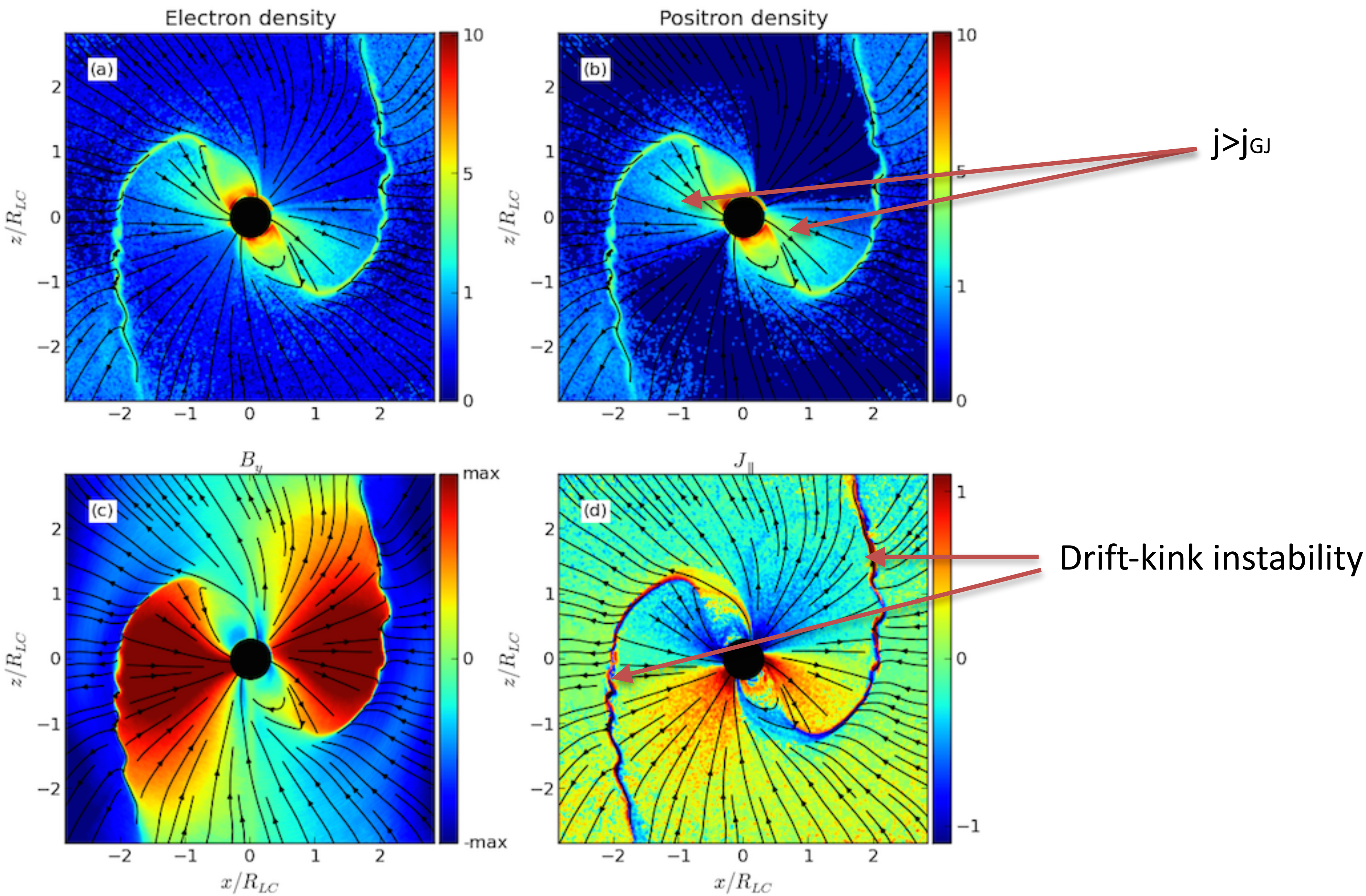


Philippov et al., ApJ, 2015

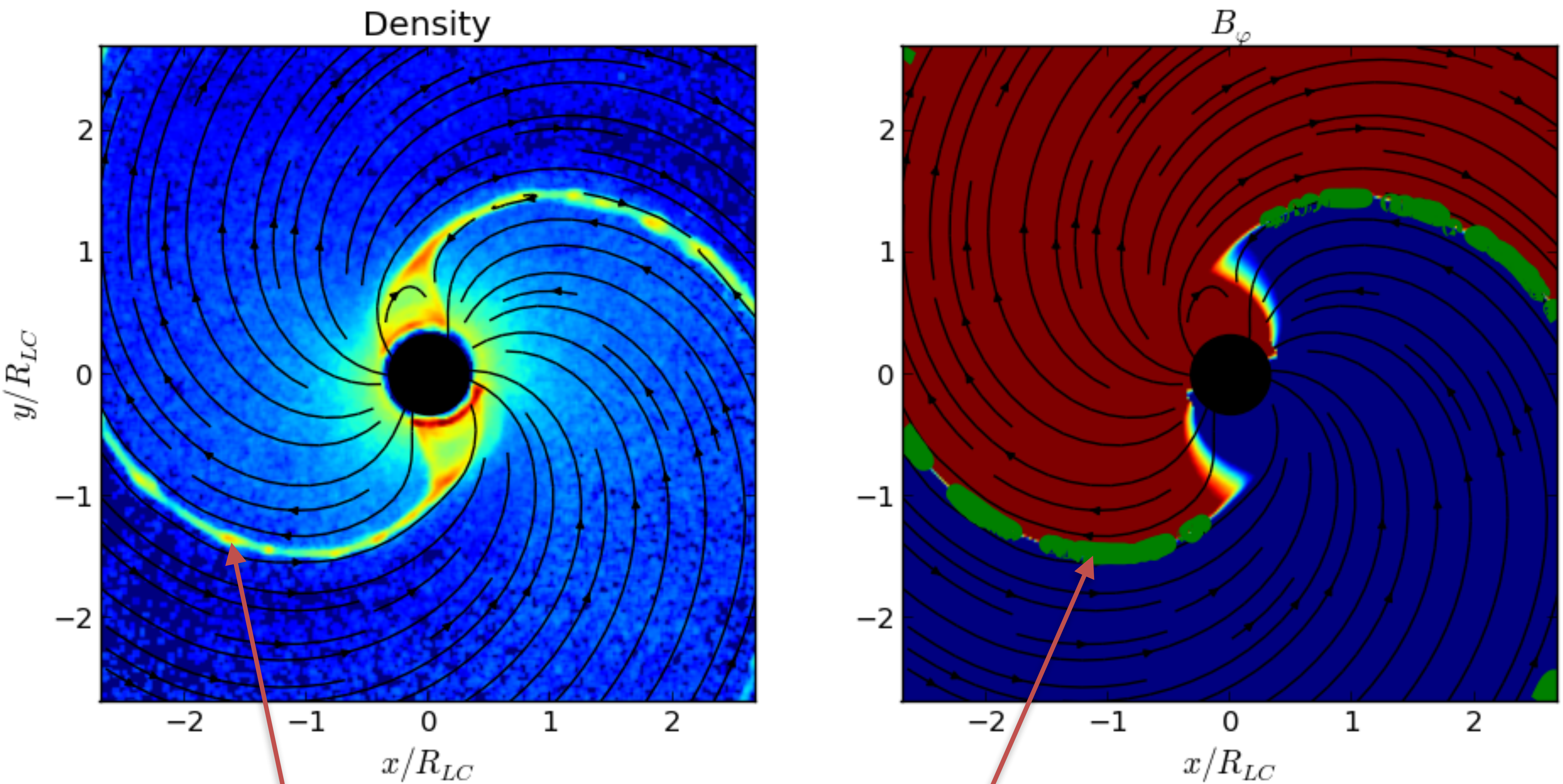


μ - Ω plane

Philippov et al., ApJ, 2015

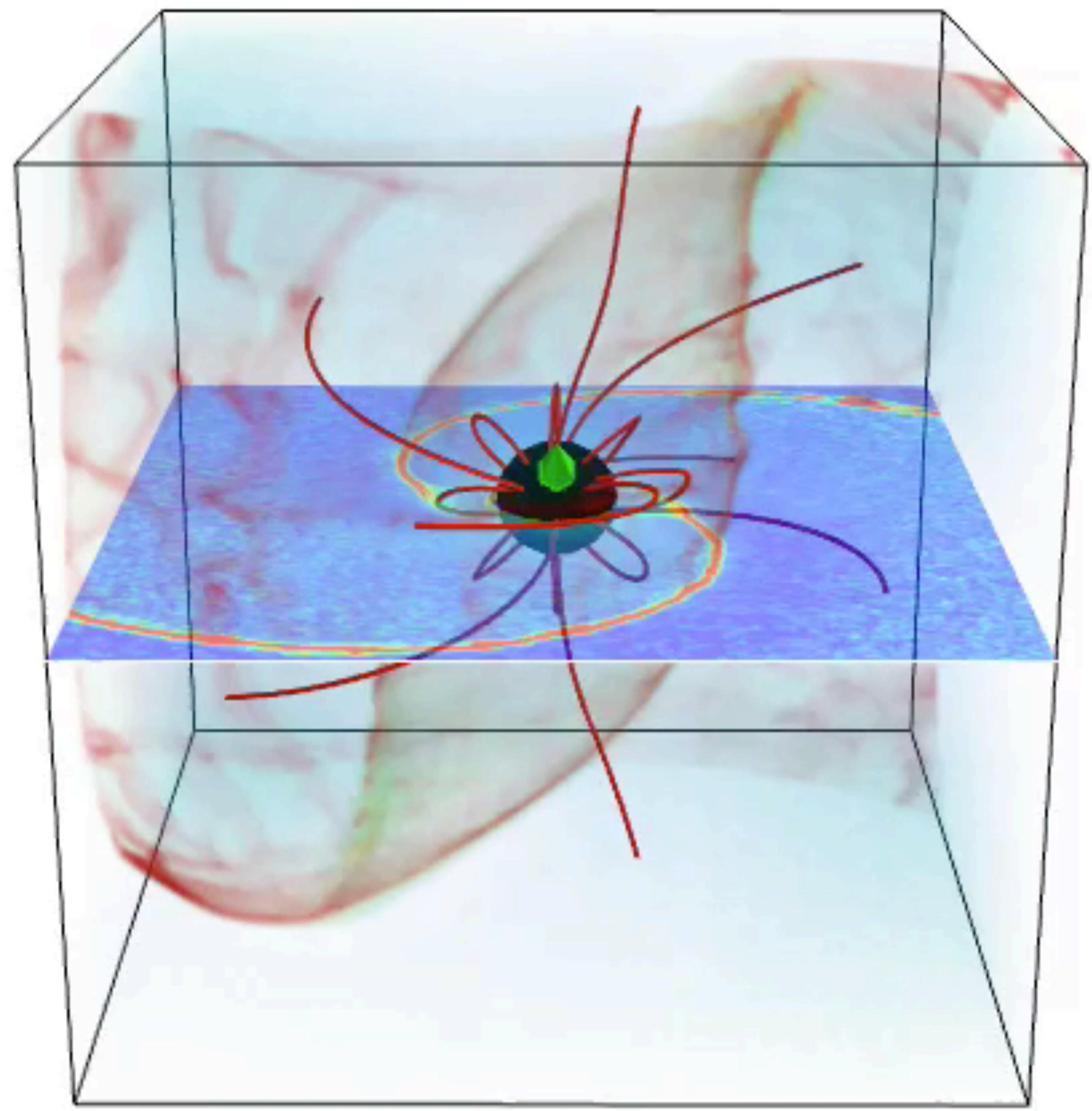


Equatorial plane



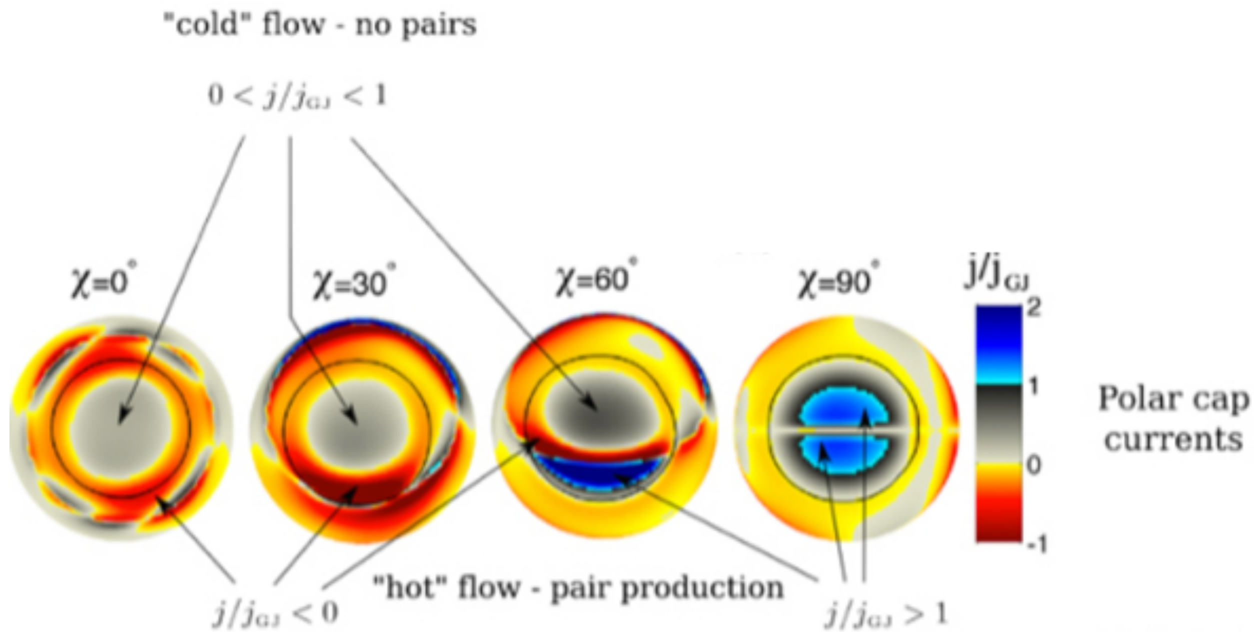
Plasmoid instability develops

E>B regions are confined to the current sheet

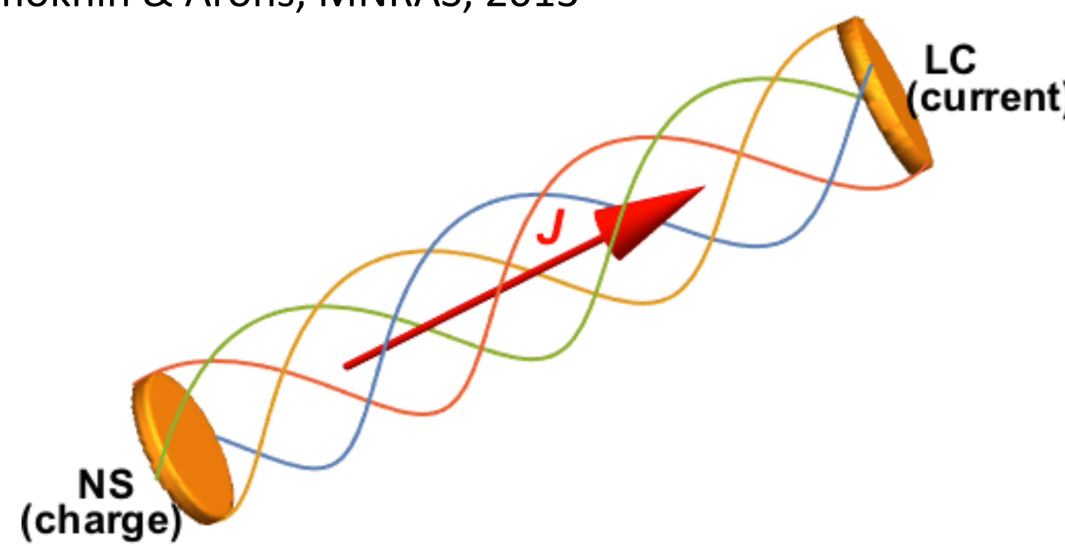


Discharge operation

- Need to sustain both charge and current density. Key quantity is $j/c\rho_{GJ}$
- If j<charge density*c, charges are advected with non-relativistic velocity
- Current is set by twist of the field lines at LC



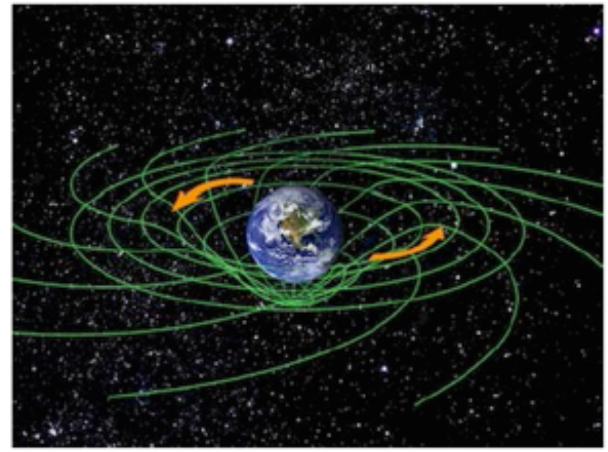
Timokhin & Arons, MNRAS, 2013

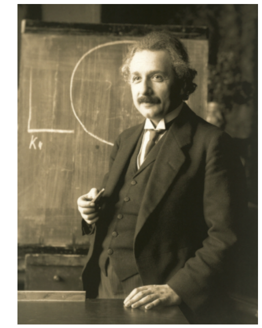


When realistic currents set by global magnetosphere are included in the simulation of polar cap discharge, we find that abundant pair production may not happen for most pulsars! Is this possible?

Prof. Einstein saves the day (1915-2015)!

Problem:
High multiplicity solutions possible only for high inclinations, but radio is observed from pulsars of all obliquities.



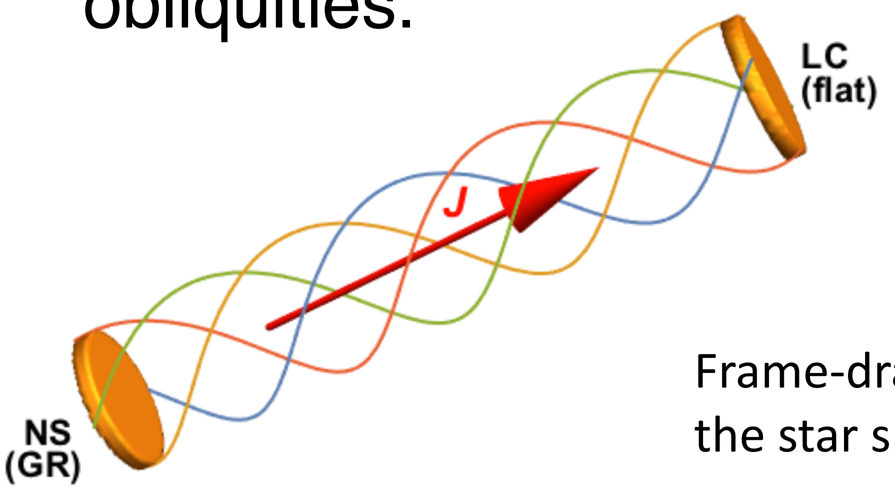


Lense-Thirring frame dragging

$$\omega_{LT} = \frac{2}{5}\Omega_* \frac{r_s}{R_*}$$

$$\nabla \times \left(\alpha \vec{E} + \boxed{\frac{\vec{\beta}}{c} \times \vec{B}} \right) = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t},$$

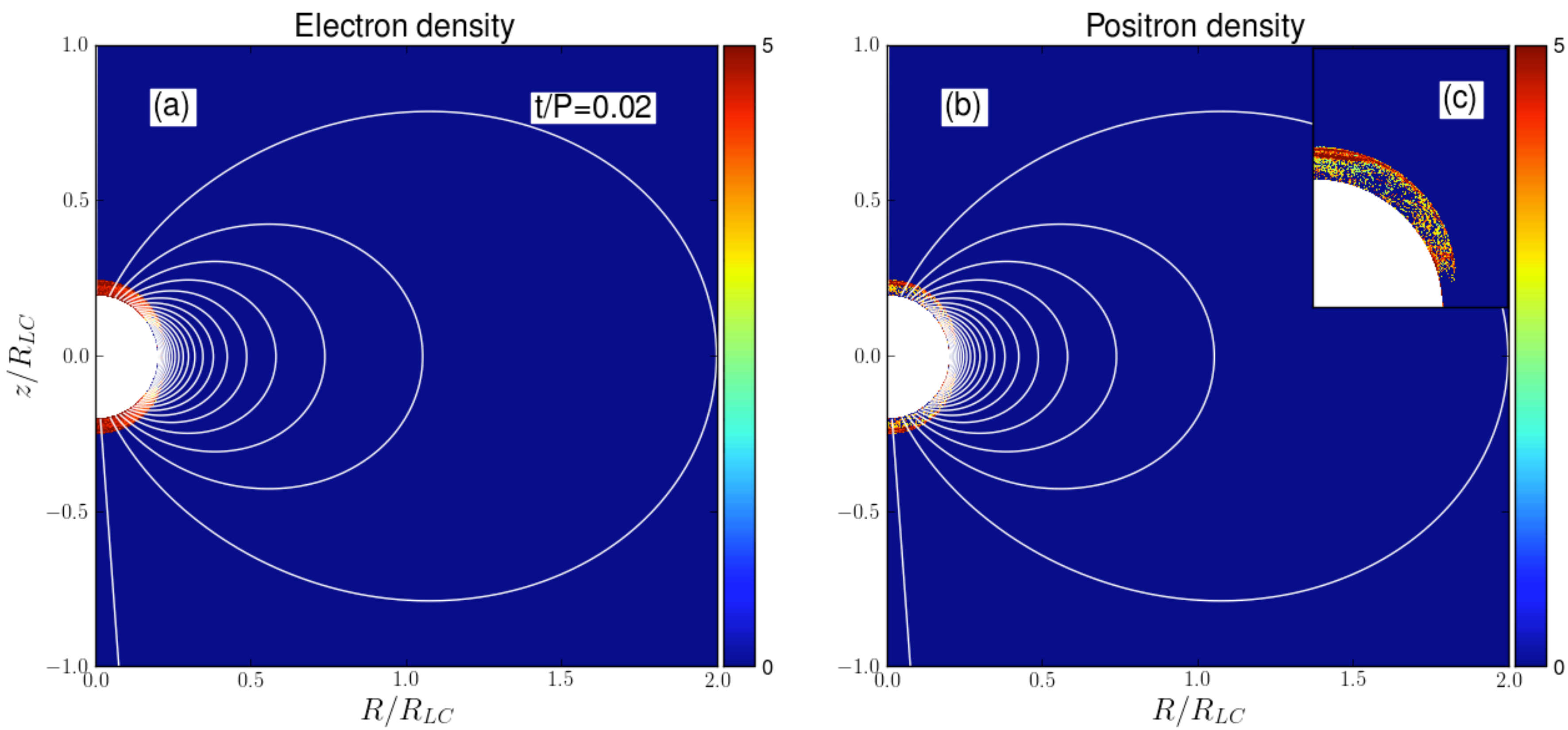
$$\nabla \times \left(\alpha \vec{B} - \frac{\vec{\beta}}{c} \times \vec{E} \right) = \frac{1}{c}\frac{\partial \vec{E}}{\partial t} + \alpha \vec{j} - \rho \vec{\beta}.$$

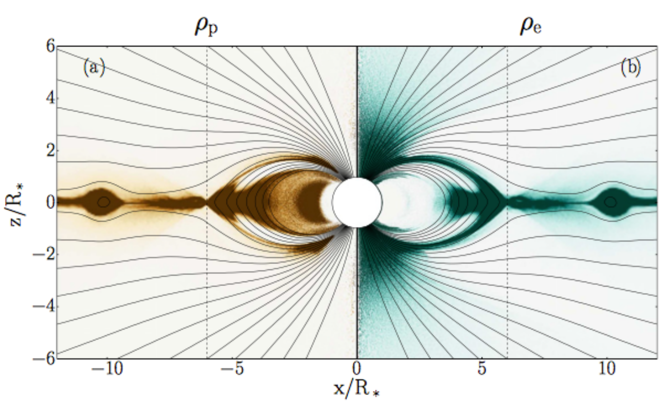


Frame-dragging makes effective rotation frequency of the star smaller close to the star (this lowers the necessary corotation charge), but the rotation is still the same far from the star (this keeps the current the same). Beskin 1990, Muslimov & Tsygan 1992

$$\frac{J_{\hat{r}}}{\rho_{GJ} c} \approx \left(\frac{J_{\hat{r}}}{\rho_{GJ} c} \right)_{\text{flat}} \frac{1}{1 - \omega_{LT}/\Omega_*}$$

GR aligned rotator





Chen & Beloborodov, ApJ, 2014

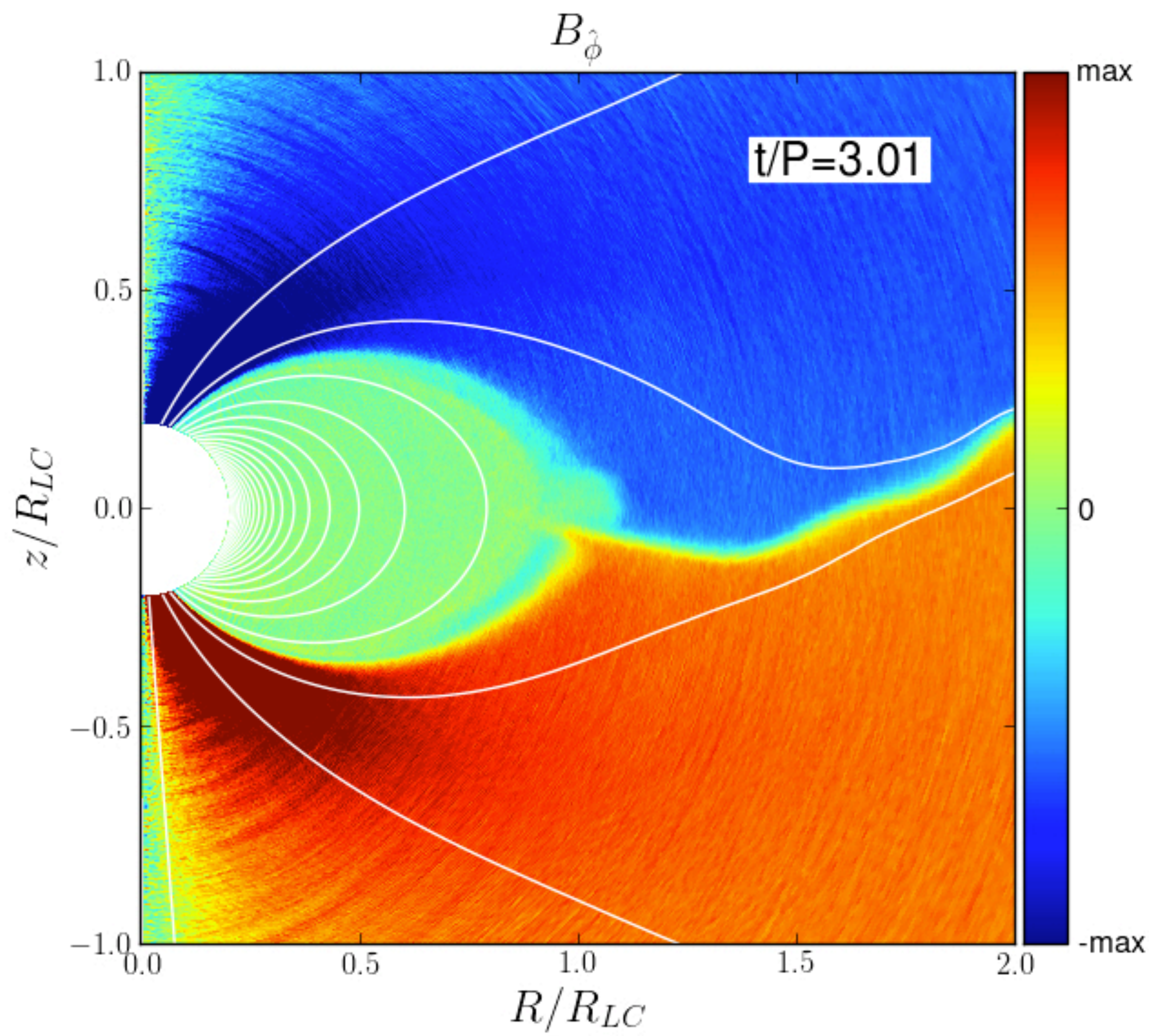
Flat space solution, no pair production

Philippov et al., 2015 ApJ

Feedback from the current sheet on polar cap pair production - implications for the radio variability?

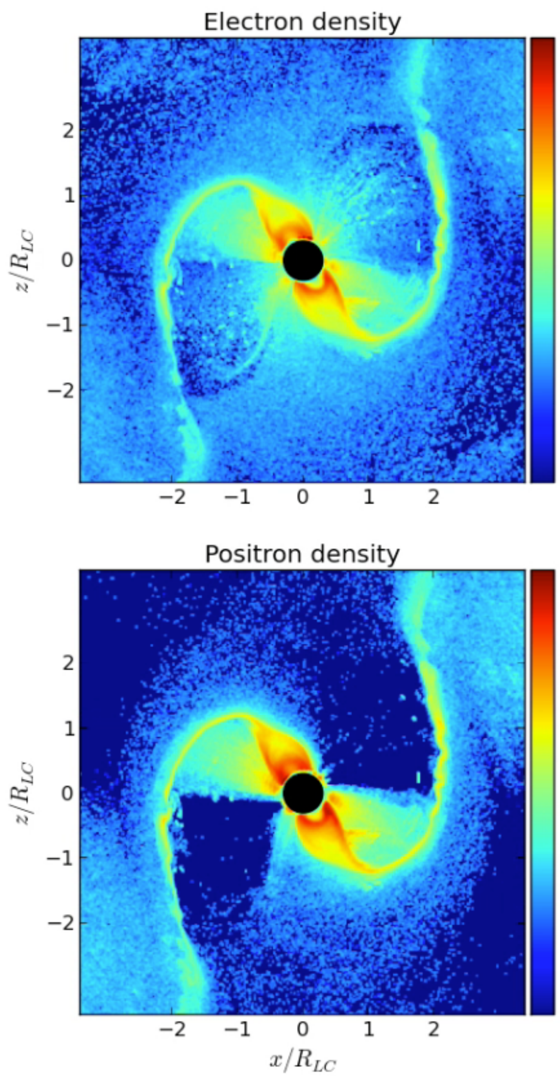
Implications for radio emission

- Non-stationary discharge drives waves in the open field zone.
- Waves are generated in the process of electric field screening by plasma clouds. They are driven by collective plasma motions, thus, coherent (see also Beloborodov 2008, Timokhin & Arons 2013)

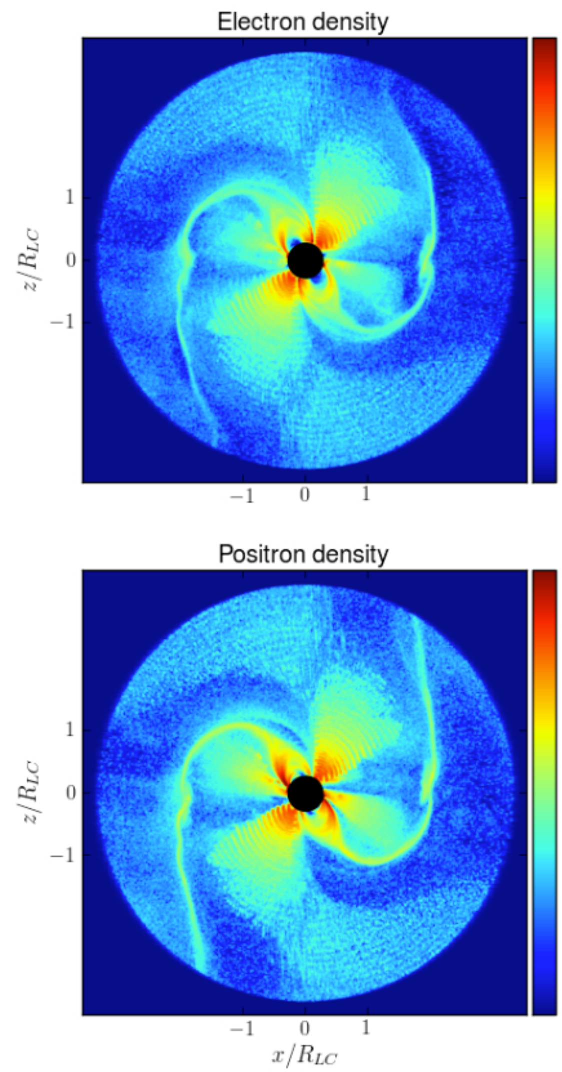


Flat space vs GR: oblique models

GR helps to establish polar pair cascade for inclined rotators!



Philippov et al., ApJ, 2015

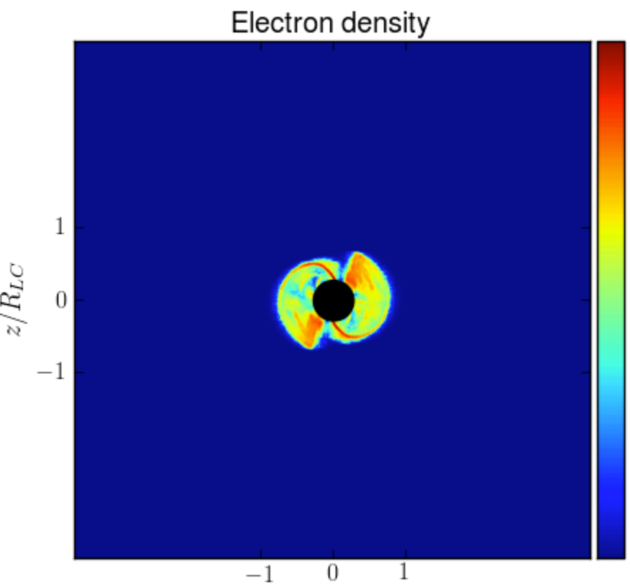


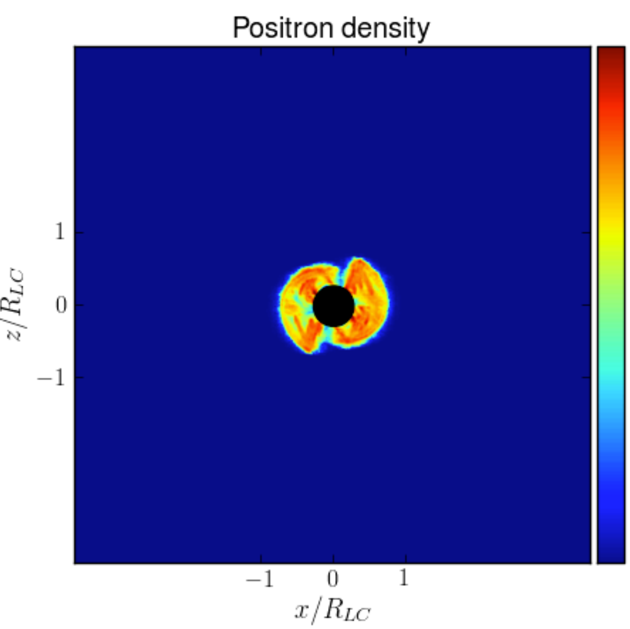
Philippov & Spitkovsky, in preparation

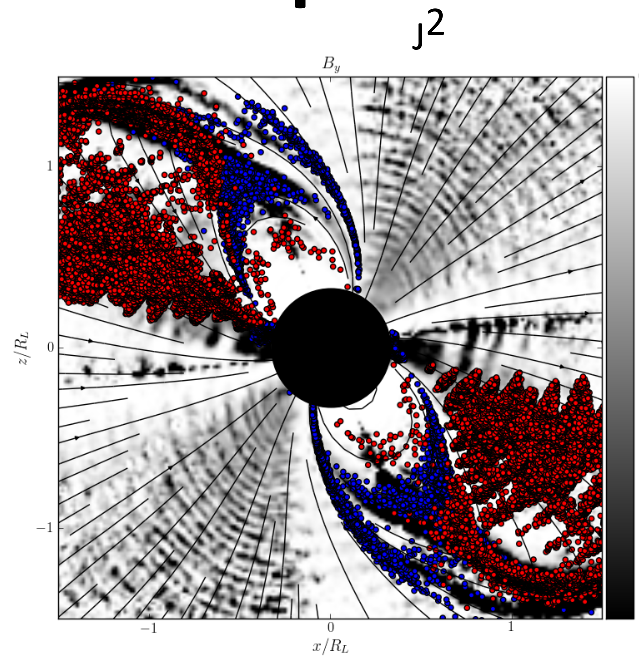
GR, radiative cooling, extraction of ions and photon propagation is included now!

$$\text{photon mfp}(r = R_{LC}) < R_{LC}$$

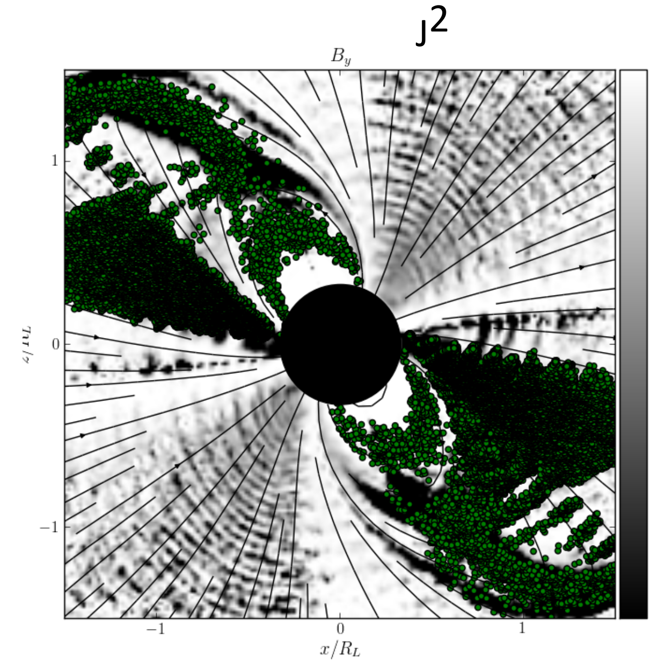
GR oblique models





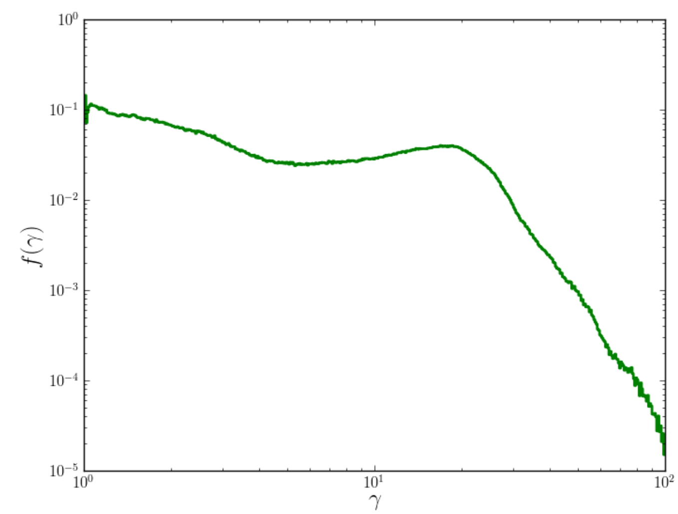


Auroral electrons and outflowing positrons



Energetic ions

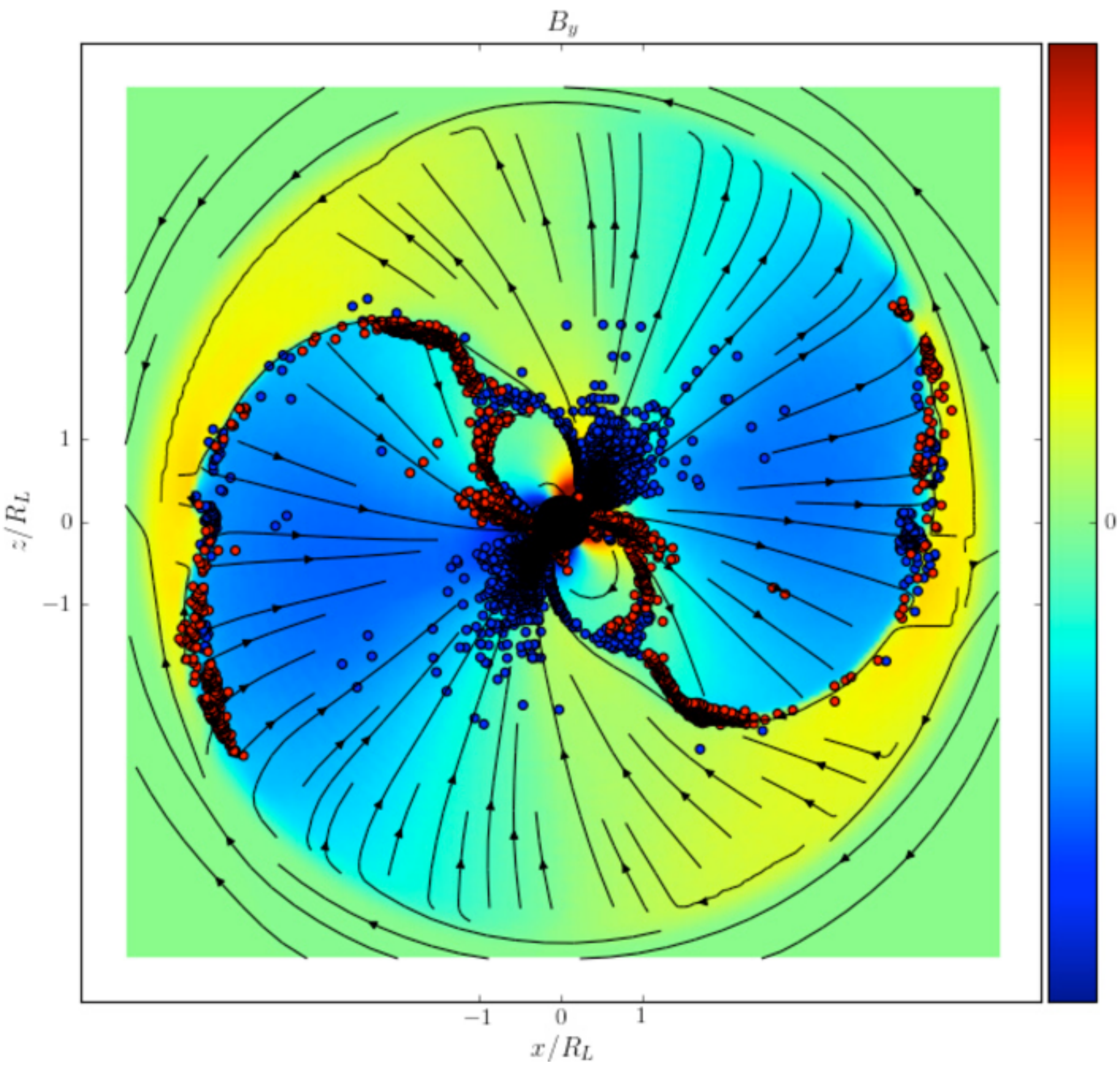
Return layer supports multi-streaming particle distribution. Contains "auroral" electrons from pair production region near the Y-point and energetic ions, extracted from the polar cap. Highest energies are reached in the current sheet.



$$\text{photon mfp}(r = R_{LC}) < R_{LC}$$

Philippov & Spitkovsky, in preparation

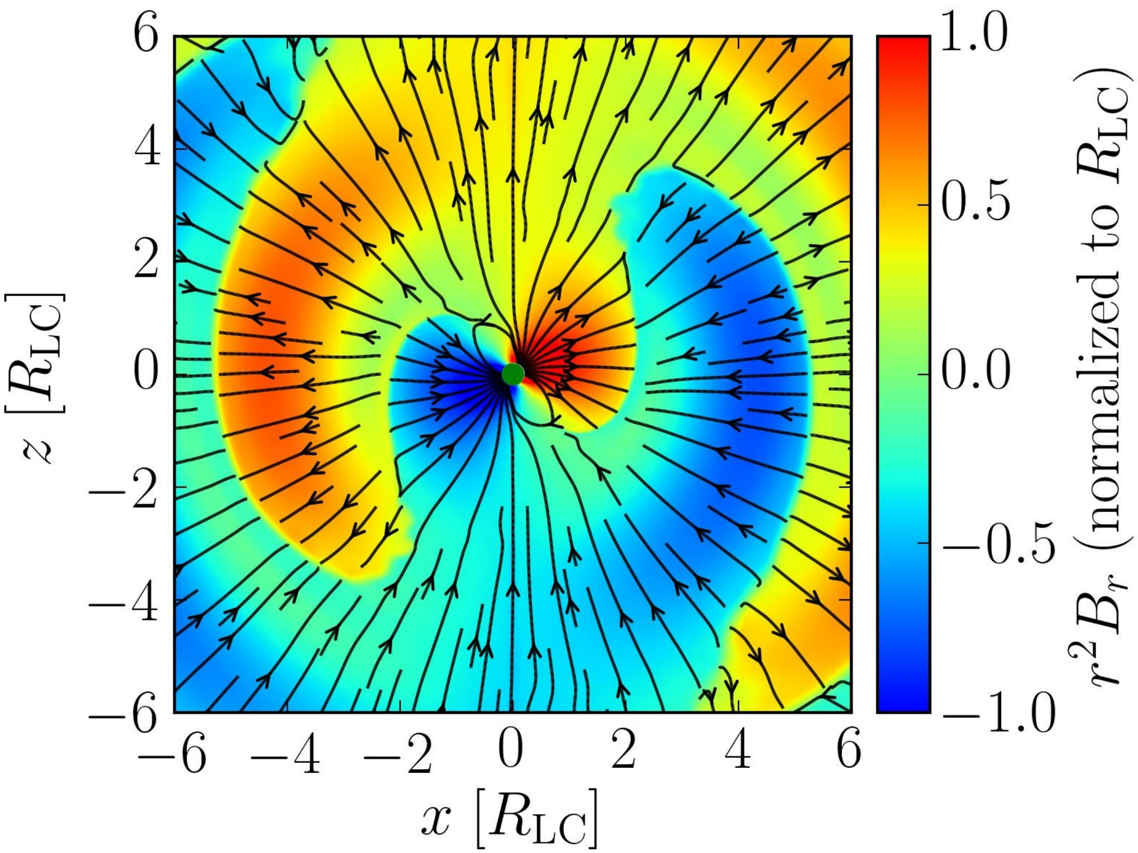
GR oblique models: where pair formation happens?



Philippov & Spitkovsky, in preparation

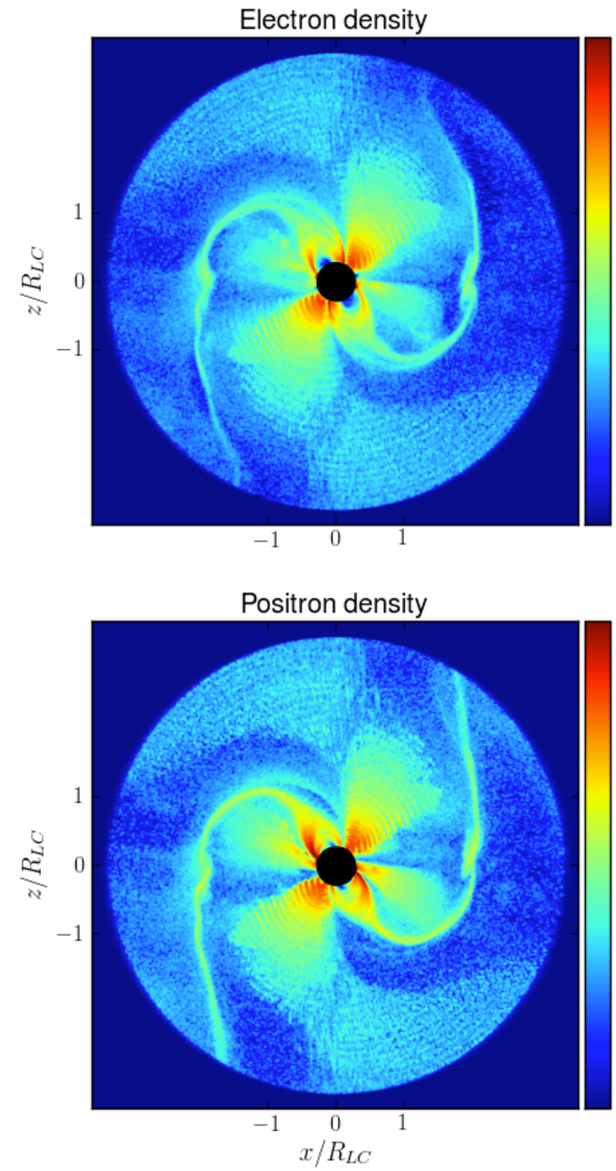
Highlights polar cap, return current layers and the current sheet. Pairs injected into the vacuum gap above the current sheet do not launch an avalanche.

Pulsar Wind



Tchekhovskoy, Philippov & Spitkovsky 2016

Not exactly a split monopole, has a non-uniform magnetic field with latitude

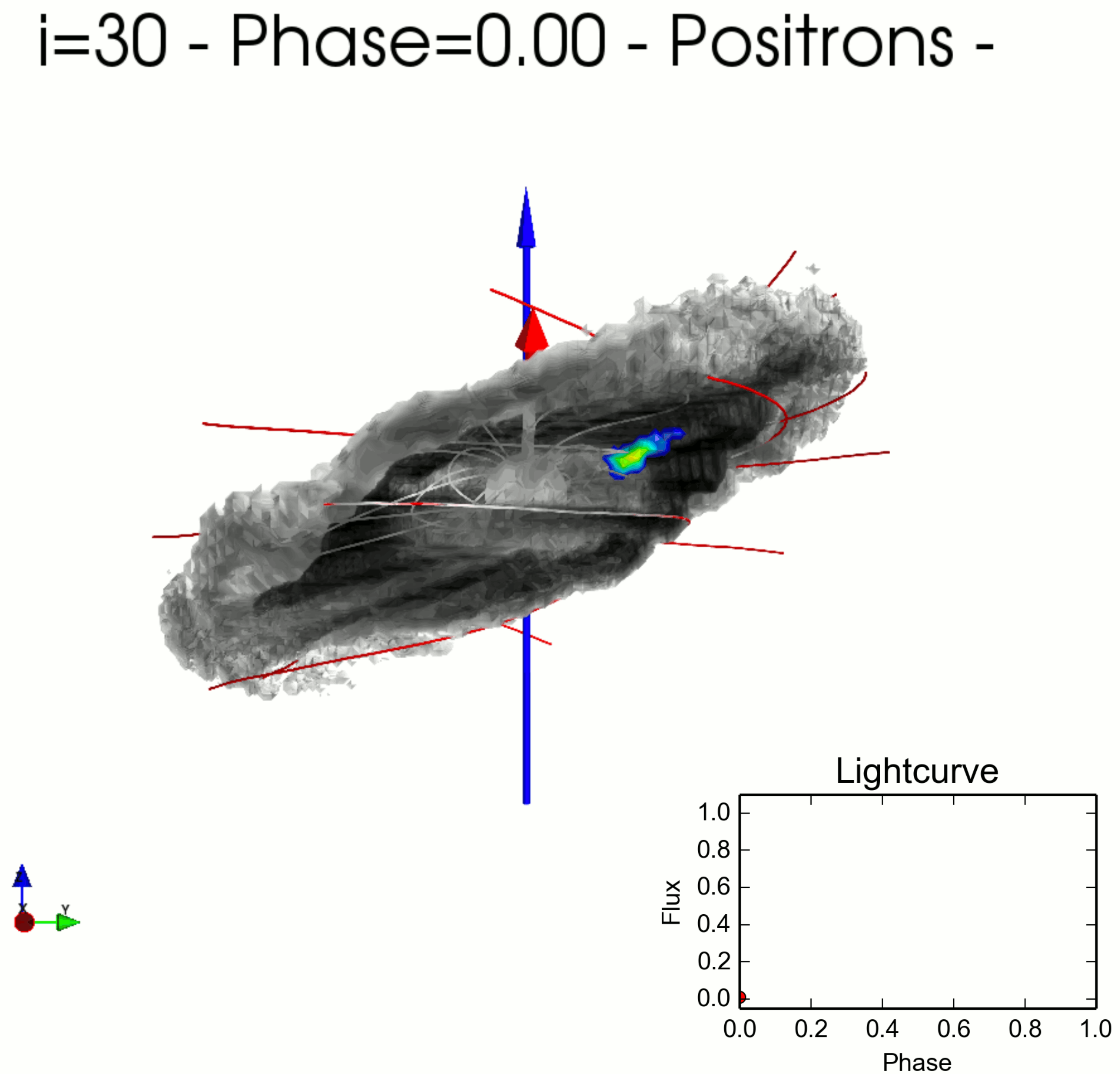


Plasma density is also highly non-uniform with latitude

Philippov & Spitkovsky, in preparation

Gamma-ray modeling

- Simulations prefer current sheet as a particle accelerator. Particles radiate synchrotron radiation.
- We apply radiative cooling on particles and collect photons.
- Observe caustic emission.
- Neutral injection at the surface.
- Predict gamma-ray efficiencies 1-20% depending on the inclination angle. Higher inclinations are much less dissipative.

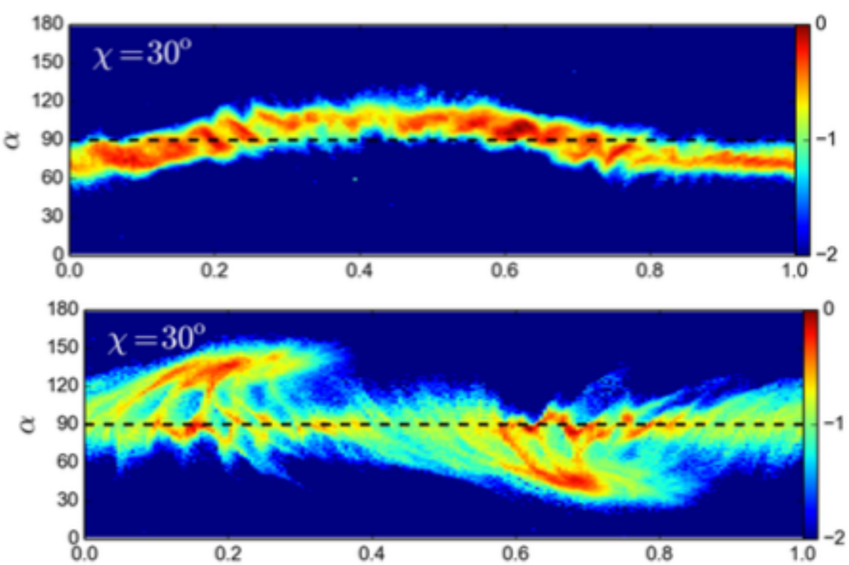


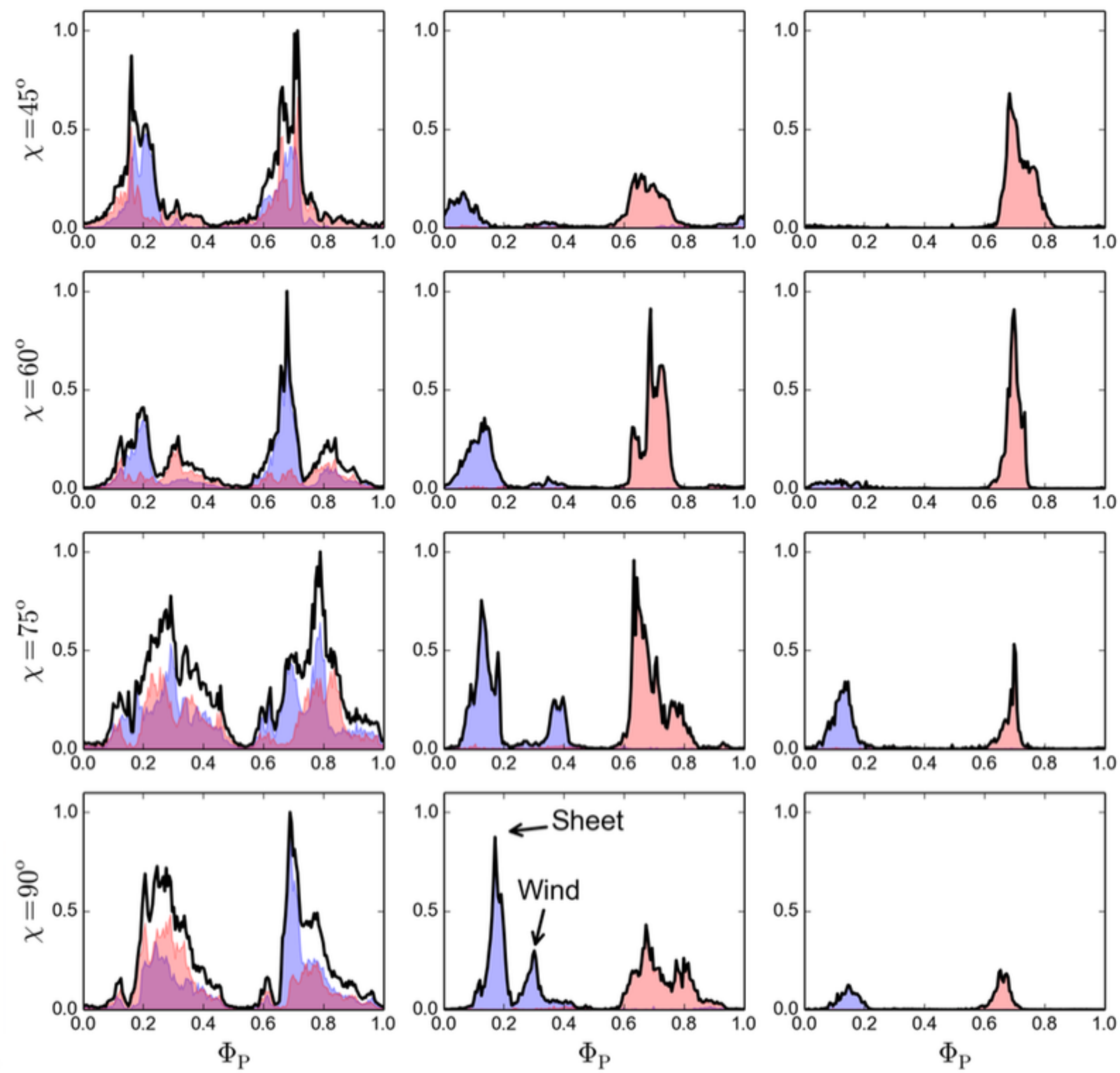
Cerutti, Philippov & Spitkovsky

MNRAS 2016

Lightcurves & spectra

- Caustic emission.
- Current sheet produces usually double peak lightcurves.





Cerutti, Philippov & Spitkovsky, MNRAS 2016

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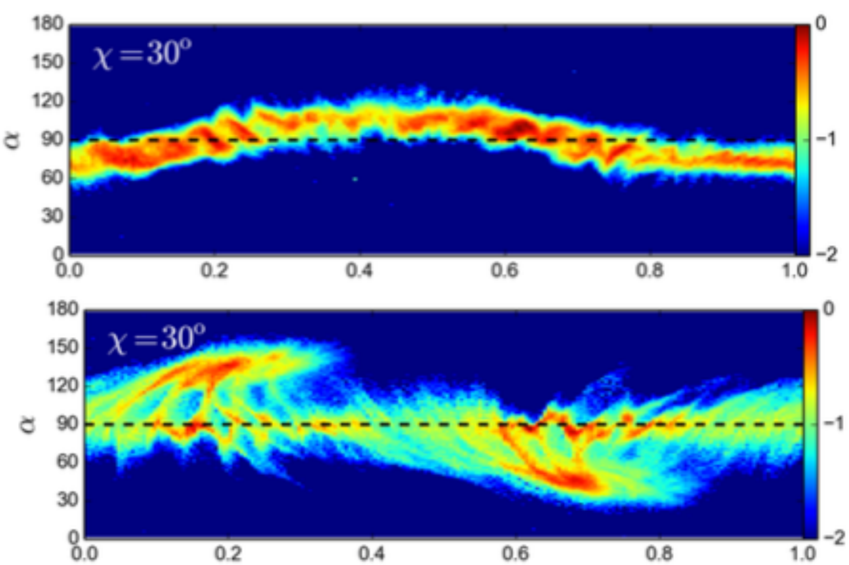
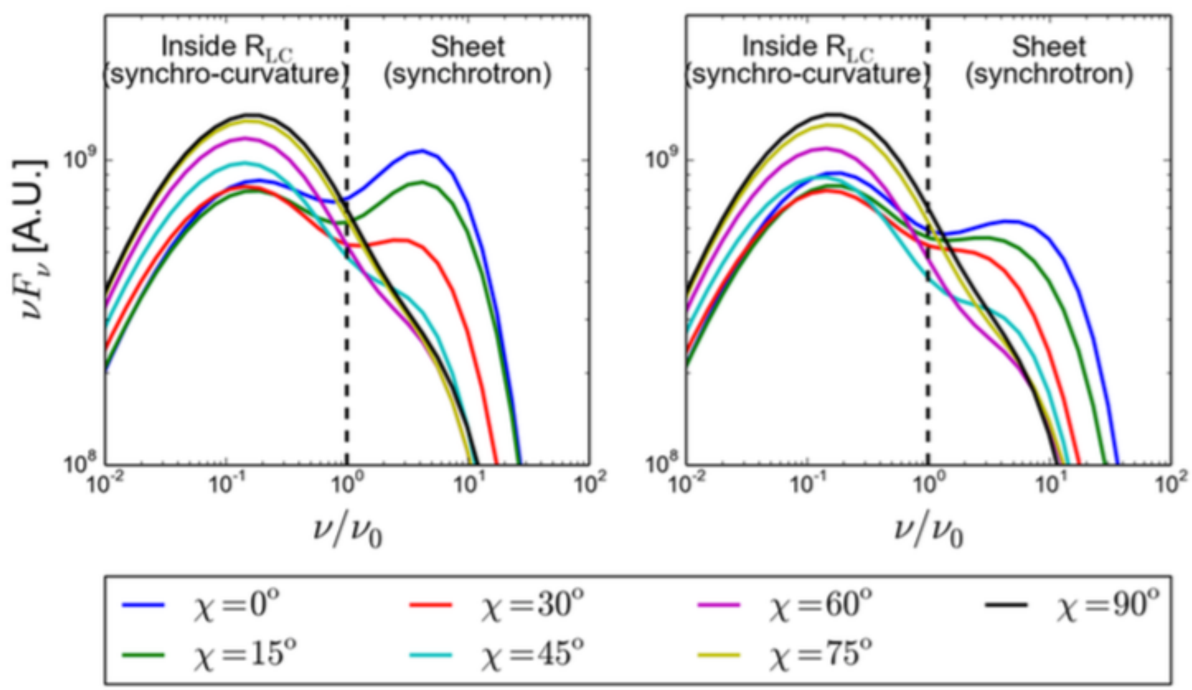


Photon spectra



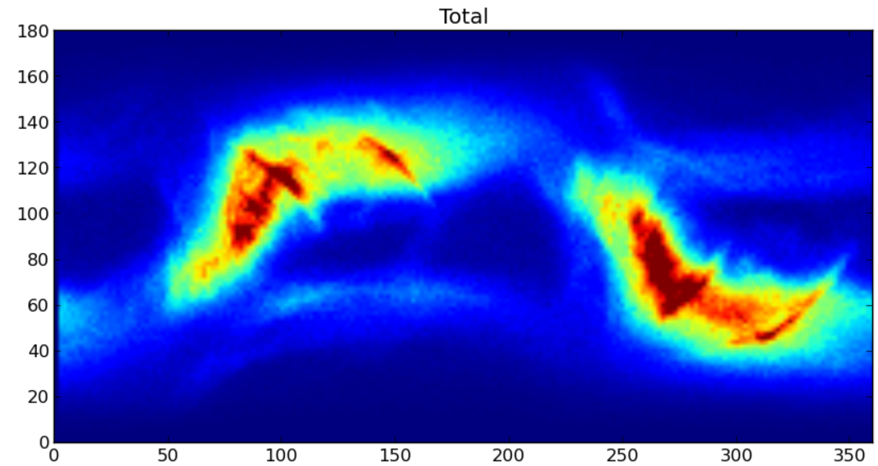
$$\nu_{\max} \approx 3e\,(0.1B_{\rm LC})\,\sigma_{\rm LC}^2/4\pi m_e c$$

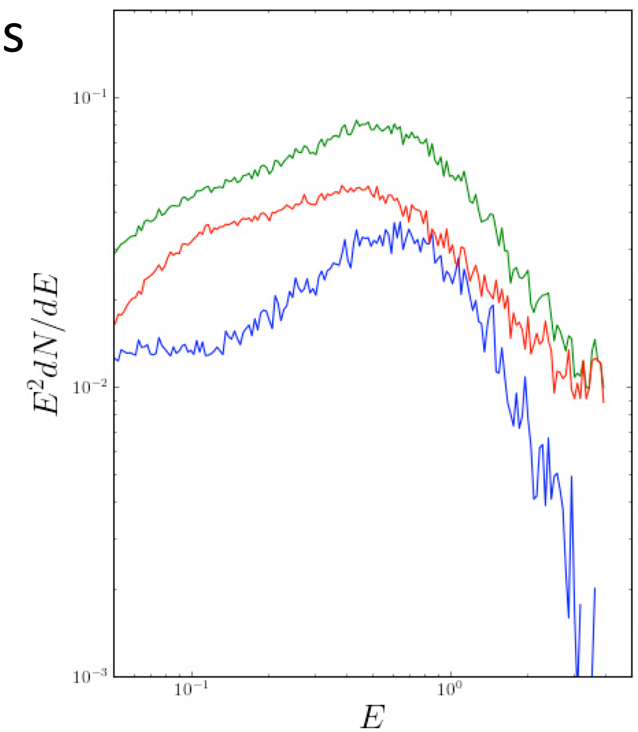
What sets the sigma parameter?

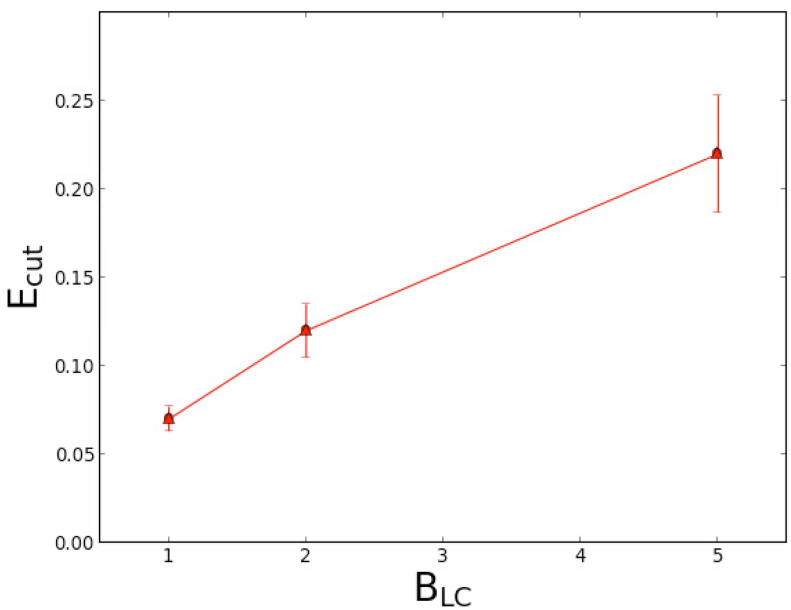
Cerutti, Philippov & Spitkovsky, MNRAS 2016

Lightcurves & spectra

- Similar lightcurves from simulations with self-consistent pair injection.
- Caustic emission.
- Current sheet produces usually double peak lightcurves.
- Pair formation in the current sheet quenches particle acceleration.
- Radiation cutoff is much less sensitive to B_{LC}.





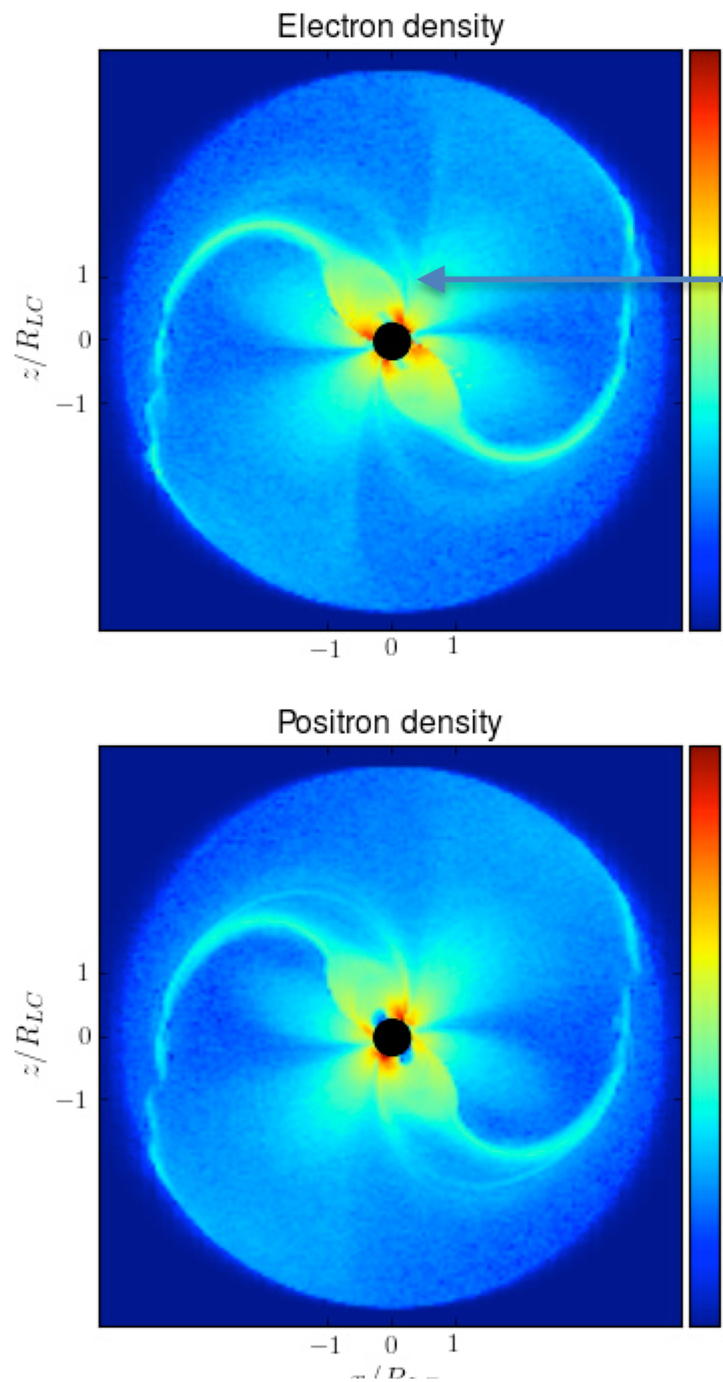


Philippov & Spitkovsky, in preparation

Anti-aligned pulsars

- Seem to be qualitatively the same as normal pulsars.
- Pair formation on field lines which extract ions start from a photon coming from outside.
- Current sheet (e.g., gamma-ray emission) seems to be the same, do the ion streams change the physics of radio?

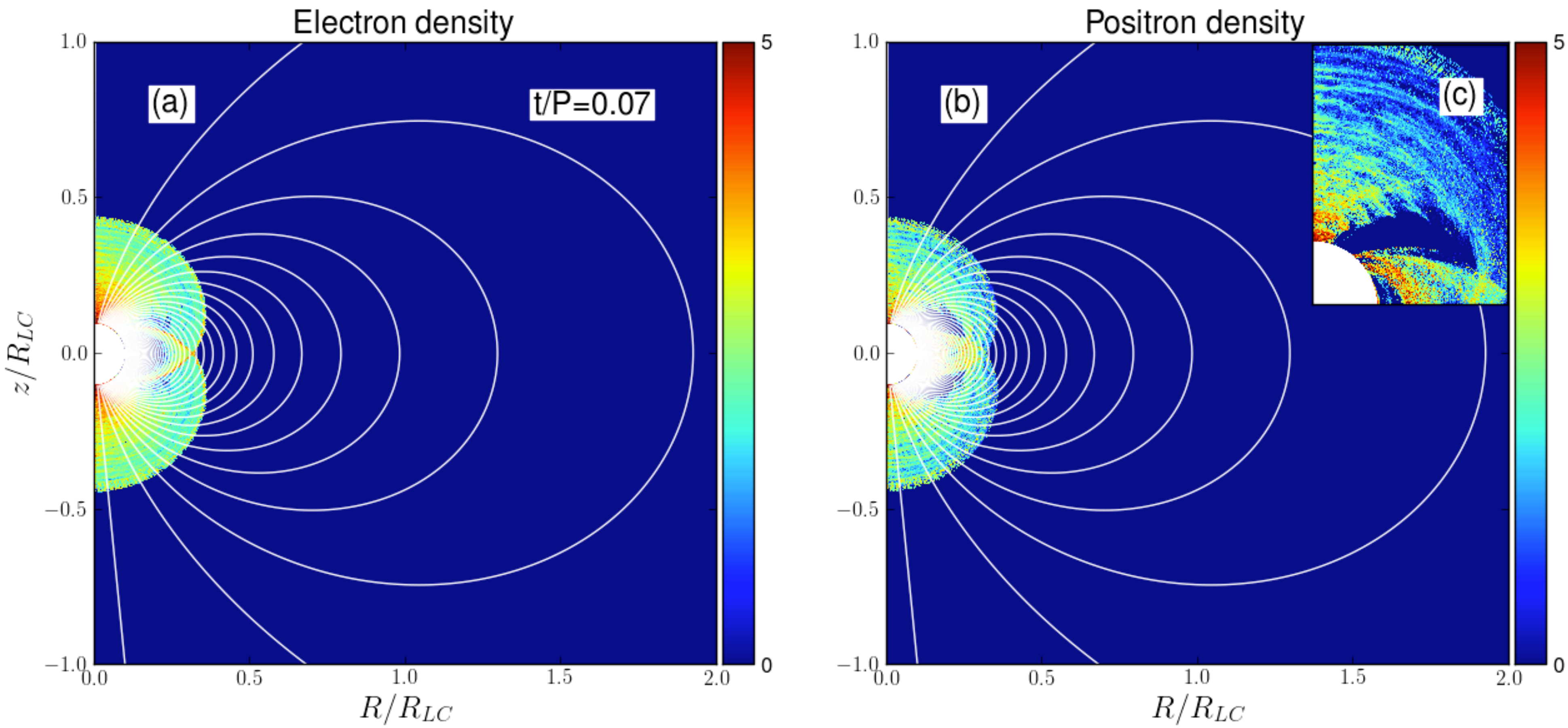
Philippov & Spitkovsky, in preparation



Ions were extracted from the surface on these field lines

Weak pulsars

What happens if pair formation is suppressed in the outer magnetosphere?



Observe oscillations around the electrosphere state with negligible spin-down, with periodic bursts of current circuit formation. Seem to be mostly “dead” pulsars most of the time. In quasi-active states current is well below the GJ current, unlikely to launch pair formation and radio emission.

Conclusions

- Origin of pulsar emission has been a puzzle since 1967 - full kinetic simulations are finally addressing this from first principles.
- In flat space, self-consistent kinetic models show that pair cascade does not operate in the polar region for small obliquities, works for >40 degrees.
- General relativity effects are essential in producing discharges in low obliquity pulsars.
- Current sheet is an effective particle accelerator. Particles in the sheet emit powerful gamma-rays mainly via synchrotron mechanism.
- Radio emission is likely caused by the non-stationary discharge at the polar cap.